REFERENCE POINTS FOR FISHERY MANAGEMENT: THEIR POTENTIAL APPLICATION TO STRADDLING AND HIGHLY MIGRATORY RESOURCES

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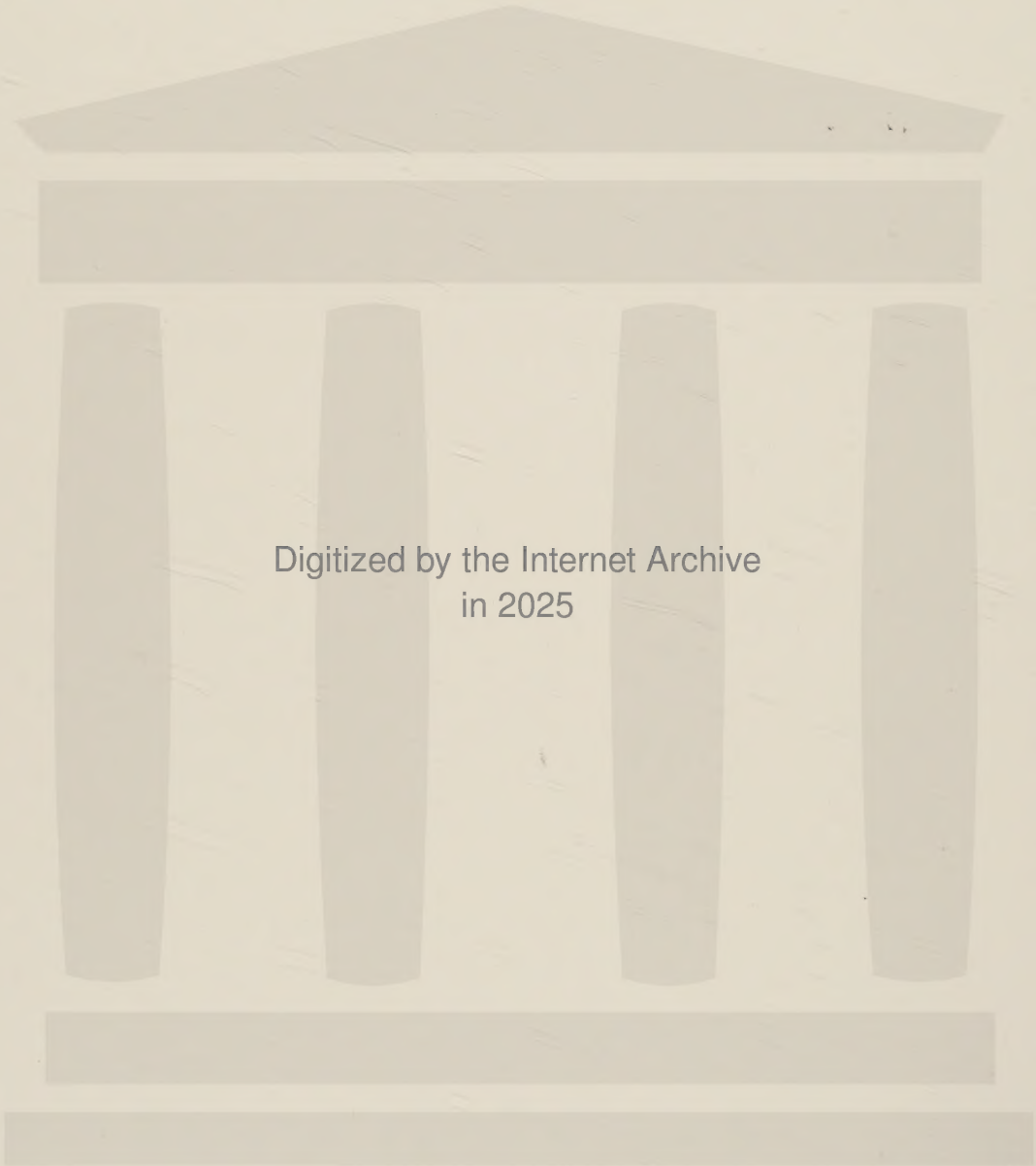

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REFERENCE POINTS FOR FISHERY MANAGEMENT: THEIR POTENTIAL APPLICATION TO STRADDLING AND HIGHLY MIGRATORY RESOURCES

FAO Fisheries Department

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 1993

PREPARATION OF THIS DOCUMENT

This document was prepared following a request from the Secretary of the United Nations Conference on Straddling Stocks and Highly Migratory Stocks after its first session in New York in June 1993, for the Organization to prepare a background paper on the subject treated by this paper. This circular is intended as a background document containing documentation of relevant issues and background papers published on this topic, and provided the basis for preparation of the official Conference paper on the same subject.

The present circular should be considered a preliminary version prepared under short time constraints, and it is intended to upgrade it before formal publication as a supporting document for managing national and international fisheries. The Organization welcomes technical comments on the present text which will be gratefully acknowledged. The review was written by J.F. Caddy, who gratefully acknowledges the inputs of colleagues, notably S. Garcia, R. Grainger, J. Majkowski and U. Wijkstrom, D. Doulman and R. McGarvey. The figures were prepared by P. Lastrico and A. Bakun.

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ABSTRACT

This document describes the technical reference points used in managing marine fishery resources, and considers the extent to which these are potentially applicable to management of straddling and highly migratory resources. The reference points are considered to be of two kinds: Target Reference Points which are management objectives representing a desirable state of the fishery, and Limit Reference Points which mark when the fishery may be entering an undesirable state. The main characteristics of each reference point are described, together with its use, the associated data and research needs, and the management context underlying its use. The review emphasizes the need to make management decisions under uncertainty as to the current state of the fishery and variable environmental conditions. The possible uses of reference points in conjunction with precautionary approaches is emphasized, as well as in the context of stock rebuilding.

The FAO Fisheries Circular is a vehicle for distribution of short or ephemeral notes, lists, etc., including provisional versions of documents to be issued later in other series.

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I. INTRODUCTION

The current management context to this paper

1. This paper was prepared by FAO at the request of the Chairman of the United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks, following its first substantive session in New York, 12-30 July 1993, as an aid to discussion by a technical working group on practical options for management of these resources, preparatory to a second session of the Conference in March 1994. In a recent review of the status of high seas, highly migratory and straddling fish stocks (FAO 1993a), it was concluded that the major problems of management and conservation are not restricted to areas within exclusive jurisdiction of coastal States, but also apply to many resources of high seas areas where effort control measures are currently fragmentary or poorly enforced, and that a large majority of so-called high seas resources fall into the categories of highly migratory or straddling stocks.

2. The conclusion that many marine fish stocks within and outside 200 miles are currently subject to ineffective management measures, applies not just to the less well known straddling resources off developing countries, but also for well-studied demersal resources of northern shelves, where recent dramatic stock declines have been registered for some important species. Relatively few straddling stocks have been exploited following uniform criteria throughout their range. Thus, in the North Atlantic and North Pacific, various classical reference points such as MSY, and $F_{0.1}$ have sometimes been adopted for stock components inside 200 miles, but the state of compliance outside national jurisdiction is often contentious or uncertain. Several highly migratory resources (notably the depleted bluefin tuna stocks) offer dramatic histories of stock decline, despite an international management history of several decades. For such large pelagic fish which fall within the 1982 Convention on the Law of the Sea (1982 Convention) category of 'highly migratory species', there have been attempts to apply threshold management measures aimed at maintaining catches at current depleted levels or avoiding further stock decline, with indifferent success. As discussed at the FAO Technical Consultation on High Seas Fisheries in 1992 (FAO 1992c), a more effective approach to setting and enforcing management targets is needed, which must be respected by all participants in the fishery, and this is an important component of the International Code of Conduct for Responsible Fishing, currently being developed by FAO (COFI 1993). While discussing the various reference points that have been proposed for management of fisheries in national and international waters, this paper also tries to place them in a management context.

The Law of the Sea context

3. The 1982 Convention (UN 1983) is the obvious starting point for discussions on international fisheries management of straddling and highly migratory stocks, and the logical points of entry for this discussion are Articles 61-64, which provide criteria for managing a stock within a single exclusive economic zone (Hayashi 1993). In Article 61, this responsibility is given to the coastal State, which is directed to take account of the best scientific evidence available, to ensure that the living resources within the EEZ are not endangered by over-exploitation, and "to maintain or restore populations of harvested

species at levels which can produce the maximum sustainable yield, as qualified by relevant environmental and economic factors". Among these factors mentioned is the interdependence of different stocks, with its implicit reference to multi-species considerations. A primary responsibility is given for protecting stocks from overexploitation, and a secondary one, referred to as 'optimal utilisation', which requires simply that the stock, when harvested, can produce the MSY. From a population dynamics perspective, this implies that fishing effort levels below that which provides the MSY are not excluded.

4. Under Article 63, shared and straddling stocks are treated together. In both cases, the States concerned, whether coastal or distant water fishing nations, should seek "either directly or through appropriate regional or subregional organizations", to agree upon the measures necessary for their conservation and development. Article 64 deals with highly migratory species, where again, the coastal State and other States whose nationals fish in the region" are urged to "cooperate directly or through appropriate international organizations with a view to ensuring conservation and promoting the objective of optimal utilization of such species...both within and beyond the exclusive economic zone". Under both of these last mentioned articles, the overall objective of conserving for optimal utilization remains by implication that given under Article 63.

5. As noted in FAO (1993a), from a technical point of view, the reference points (RPs) for straddling and highly migratory stocks do not differ from those for shared stocks (Gulland 1984; Caddy 1982), or for those occurring entirely within an EEZ. Thus this paper draws freely upon literature for RP management in both wholly proprietary stocks of EEZs, as well as citing relevant literature for shared stocks. The feasibility of application of individual reference points may differ, and will be discussed in the course of this paper. Where active migration between different jurisdictions requires particular management approaches to be adopted, these are noted as particularly relevant to highly migratory resources and some migratory straddling stocks.

II. SOME IMPLICATIONS OF THE CONCEPT OF A 'REFERENCE POINT'

6. **For the purposes of this paper, a Reference Point will be considered as a conventional value derived from technical analysis which represents a state of the fishery or population whose characteristics are believed to be useful for the management of the unit stock in question.** Referring to Reference Points as Conventional Values reflects their frequent specification without variance terms, and it is worth noting here that before being put forward as reference points, all of the model-based variables, and the parameters they are derived from, are only known approximately, often with a poorly-defined level of error. What was noted for MSY by Wallace (1975), is valid for all reference points, namely, "MSY is not the management regime, and in the past we have confused the difference between the tool for management and the actual management of the resource itself!"

7. Fishery management then is not synonymous with the attainment or otherwise of a single reference point, and this idea will be developed later in the paper. The

philosophy that an overall objective can be defined for a fishery that incorporates all important factors, was reflected in the 1958 Oceans Convention formulated under United Nations auspices in Geneva, where the term "Optimal Sustainable Yield" was invoked. Optimal Yield (OY) has since been variously defined as allowing for inputs of "economic, social and biological values"...."rather than being limited to maximizing net profits or maximizing sustainable yield" (Wallace 1975). From the perspective of this paper, since it has no single technical definition, OY is not considered a technical reference point, but may be an overall criterion which is satisfied when the fishery remains within a safe and productive area defined by a number of the technical reference points described later in the paper. The Reference Points used in fish stock assessment are largely based on population models and hence on mathematics, and can be difficult to assimilate for the non-technical reader. Annex I presents a few key concepts.

Information needs for fishery management using RPs

8. The relationship between stock size and fishing effort is not always easily defined, and can be modified by environmental conditions which can change the stock's availability to fishing, its vulnerability, and hence the effective fishing power of a fleet fishing the resource (FAO 1984). It is not only important to consider the effect of managing according to these reference points, but also to consider the consequences of making the wrong decision under the conditions of uncertainty that apply to management of all fisheries.

9. To know that an optimum has been reached requires continuous statistical monitoring of the catch, the effort, and a range of biological and economic criteria, but also a realistic appreciation that the actual values for these criteria will only be known with low precision. Given that marine fish populations are not visible for direct census, there will be a significant error in our best estimates of biomass, as well as errors in our estimates of catch and fishing effort. These errors, whether due to experimental error in surveys, the use of the incorrect models, misreporting or non-reporting of catches, all will affect the estimate of stock size at the end of any year, and what is available for harvesting the next. A knowledge of the abundance of the new year class entering the population is also highly desirable if a forecast of landing levels with the given fleet size is required, or if we need to know the appropriate level of removals with the given fleet size that will not affect spawning in future years. Unfortunately, although analytical models incorporating growth and mortality rates, age at first capture etc., are widely used in 'developed' country fisheries in high latitudes (see, e.g. ICES 1993), the data upon which to base an estimate of current age structure of the fish population (such as by age-reading from otoliths) are not available for many tropical species, or are labour and technology intensive. Where assessments have been performed, many of them still depend on low precision approaches and sparse or inaccurate data, making management by reference point problematical, and precautionary approaches to avoiding stock collapse mandatory.

10. Maintaining systems for collecting and storing fishery information from all parties, and carrying out fisheries surveys and research, are integral parts of establishing whether management targets are being met, and of evaluating the effectiveness and impact of such measures. It is not unreasonable that as a condition for receiving a commercial

fishing licence, fishermen provide accurate information on the location, type and time of catches, and fishing effort. This information can be gathered through logbook systems, by port interviews with fishery officers, by on-board observers, radio reporting and at-sea inspection, and possibly in the future, through black box monitoring via satellite of the position of fishing vessels and the operation of their mechanical equipment.

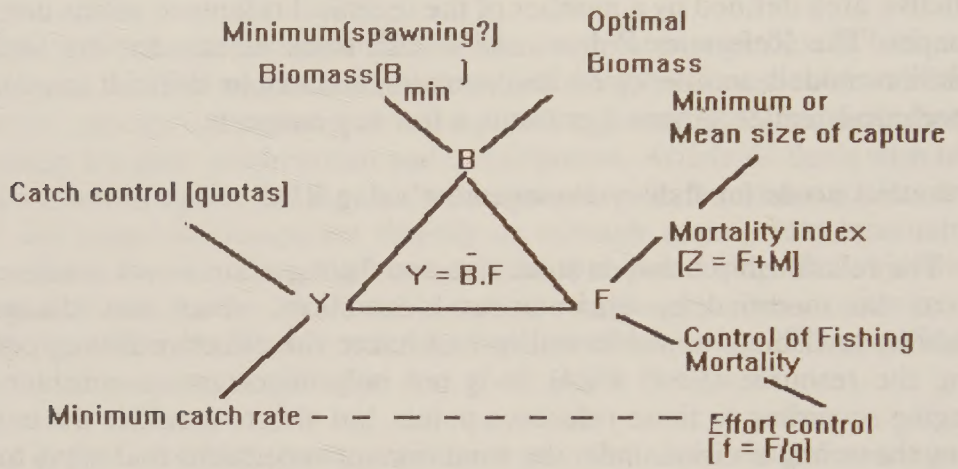

Fig 1: The main population variables used in defining biological reference points. In addition to the three primary measures of the state of an exploited population (Fishing mortality rate, [F]; Biomass, [B] and Yield [Y] whose interrelationship is specified in a catch equation), other secondary measures shown may have some validity as Reference Points.

Establishing the position of the fishery relative to the Reference Point chosen

11. Briefly put the procedure for establishing a reference point is that of:

(a) agreeing on how fisheries yield varies for the whole stock with total standard effort/fishing mortality applied by all fleets under a given fishing regime (mesh size, closed seasons/areas, etc.);

(b) deciding on a suitable RP as a long-term management objective, and the total yield and fishing mortality/effort it corresponds to, and agreeing on a series of limits or thresholds when the stock is considered to be in danger of overexploitation, and on pre-established management responses when these are reached;

(c) establishing the current 'status quo' of the fishery by analysis of fishery statistics and biological research, in terms of control variable(s) chosen, such as the fishing mortality rate (F), biomass (B), and yield (Y) (Fig 1). [Current values of these

variables will be referred to in the text as B_{NOW}, F_{NOW} , and Y_{NOW}]. These estimates should ideally be accompanied by at least a rough estimate of their likely error of estimation;

(d) negotiating allocations from this reference point, either in terms of yield, or equivalent level of fishing mortality and fishing effort to be applied, for all participants;

(e) agreeing on a 'set of rules' for management of the fishery.

(f) establishing if the long-term reference point is appropriate in the short term, or if stock rebuilding is needed. In the latter case, deciding on a long-term strategy for stock rebuilding.

12. As recognized under UNCLOS, the above activities need to be carried out in cooperation with all parties, with exchange and pooling of data as preconditions for any scientific management of a straddling or highly migratory stock. It is a risky strategy for any participant to test if an RP is being met from their data alone (Annex I).

Underlying data requirements for calculating reference points

13. Reference points discussed in this paper will depend on three main modes of investigating the status of fisheries:

14. **Analysis of commercial fisheries data:** The underlying data are catch and fishing effort, and biological samples of the catch for length or age determination for analysis of fishing mortality and yield relationships. If only catch and effort data are available, a production model assessment may still be used, but with caution in absence of size and age-related abundances. Where the newly recruited, or earlier prerecruited, age classes are available to sampling by special gear, this adds an index of recruitment abundance which is useful for future catch projections. If the data incorporate a statistically valid sampling of the catch then each year a new data point is added; given a knowledge of the natural mortality rate, they can be used for reconstructing past fishing mortality rates and cohort sizes, employing Cohort Analysis. Where management is by effort control, standardization of fishing effort units between fleets with different fishing power characteristics must precede allocations in terms of days fishing and/or numbers of fishing units. Some typical measures of the accuracy with which population variables yield and fishing mortality are provided in Table 1.

Table 1: Some likely magnitudes of errors for quantities used in developed country assessments of the status quo of shelf fisheries: (c.v. = coefficient of variation = one standard deviation/mean value)[1]

VARIABLE	DATA SOURCE	C.V. VALUES (RANGES)				REMARKS
		10%	10-20%	20-30%	30%+	
Annual catch	commercial statistics		✓			Significant bias (discards/under-reporting)
Catch rate	commercial statistics	✓	✓			" "
Catch-at-age	sampling survey	✓	✓			Requires sample survey commercial catches
Survey for biomass	bottom trawl			✓	✓	Improves with repetition
"	acoustic (small pelagic fish)			✓	✓	" " "
Fishing mortality rate	cohort analysis, etc.		✓	✓	✓	Few estimates published
Natural mortality rate (M)	catch curves, etc.					Few direct estimates: many assessments employ values from other stocks

15. **Research vessel surveys:** experience in many developed country fisheries has shown that fish stock assessments based on commercial data alone are susceptible to several significant sources of error and bias caused by misreporting and by 'hidden' increases in the fishing power of boats. This can mean that a given catch rate maintained from year to year may in fact disguises a stock decline. The use of a standard fishing survey with a standard boat and randomized stations can provide objective data on stock size, which is less liable to biases than catch data, even though most survey biomass estimates also have a relatively high variance. Table 1 includes some very tentative estimates of the likely range of errors in various population variables for well-studied offshore fish stocks, largely based on the literature cited in this circular, and on other publications such as ICES Research Reports.

16. Presumably for highly migratory species (HMS) which are difficult to survey (and to determine their age), research surveys are rarely possible, and stock size estimates

[1] There is an 85% chance that the variable lies within one standard deviation of its mean value: thus, if for the biomass, the c.v. = 30%, and mean value 100 t, there is an 85% chance that the mean lies between 70 and 130 t.

have even higher levels of error. Researchers may have to concentrate on tag and recapture data for mortality or exploitation rate determination. Otherwise, the fishery reference points may place heavy reliance on season- and area-specific catch rates in estimating changes in stock size.

17. **Fish stock assessment and uncertainty:** The assessments of fish stocks presented to management fora are characterized by the use of standard "accepted" procedures which, once adopted, are only changed when evidence for a clear improvement in methodology is accepted by all parties in a multinational stock assessment working group. In this sense, the methods used (and often the parameter values accepted) acquire a conventional character which indirectly reflects the level of uncertainty of current estimates of the current situation of a fishery. A 'standard method' has often been shown later to have a degree of bias in estimating current biomass and fishing rate, but can still be valuable if this level of bias is constant, allowing population trends to be followed from year to year. A commission may still choose to base management action on such a methodology in managing relative to a reference point, if the results are shown by experience to correspond to a robust condition of the population in question. Although explicit estimates of accuracy or precision are rare in the literature, some 'qualified guesses' of the likely order of the error are presented in Table 1, mainly for well-studied groundfish populations of shelf areas (with the exception of the acoustic estimate). These 'guesstimates' are open to question for any particular fishery, and are likely to be significant underestimates for pelagic and large pelagic fish stocks. They were derived from as yet unpublished contributions to the conferences mentioned in the footnote to "References". The magnitude and uncertainty of these estimates should be borne in mind in deciding on management according to any given reference point.

18. Three important points should be made here:

(a) From the values in the above table it is clear that the current stock size and fishing mortality are known with relatively low accuracy in most fisheries, although with a history of past assessments the above estimates may improve somewhat. Total yield may appear to be known with a higher precision than other variables, but often suffers from high or unknown biases due to discarding and misreporting, particularly if management is by quotas. Survey estimates of biomass typically have a higher variance, but may be less biased, and improve with research investment. In all cases, the relative change from year to year will be known with more precision than the absolute value.

(b) Management targets with equal levels of risk will require lower levels of removals and more conservative RPs if statistical data is poor and non-reporting or misreporting is the case, than if proper attention is paid to data gathering.

(c) In order to reduce the risk of error in determining the present position of the fishery relative to the RP, two or more different stock assessments, using independent data sets will be necessary, but the exact status quo for the fishery is unlikely to be known with an accuracy of more than ± 10-30%, even with a high expenditure on research.

Reference points as targets, floors or ceilings, or qualitative criteria?

19. As noted in Annex I and Fig 1, the primary population variable measuring impacts on an exploited stock is the effect of fishing as measured by the fishing mortality rate (F). Added to the natural mortality rate (M) due to predation, disease, etc., this equals the total mortality rate (Z) to which the population is subject. The biomass (B) is another primary measure, which may or may not support a safe level of yield (Y). In a sense, the annual yield, the fishing effort and catch rate are secondary measures of the impact of the fishery on the stock, since they depend on knowing their relationship to the above primary measures. Nonetheless, all of the measures in Fig 1 may, under certain constraints, be used as reference points, although for uniformity of presentation, in this paper all reference points will be expressed in terms of their equivalent fishing mortality rate, F. It is important, however, to remember that this F value corresponds to a given ratio of Yield/Biomass for the stock in question.

20. Simply making a list of possible technical reference points suggested here for rational exploitation of a fishery resource does not of itself assist in evaluating them, and before describing the possible reference points, it will be important to categorize them, and discuss their management context. Traditionally, RPs have been considered desirable targets for management, it being assumed that it is possible to 'tune' the fishery so that one or more control variables (e.g. total annual catch and standard fishing effort/mortality) as determined from fisheries statistics, are believed to be close to a preset RP. Such a target for management can be referred to for convenience as a TRP or Target Reference Point, and MSY has classically been used in this sense. It must be stressed that no TRP proposed to date is stable, such that the fishery gravitates to this point automatically, or returns to it if disturbed. Indeed, TRP management requires active monitoring and continual readjustment of management measures on an annual time scale since, as we have seen, there is usually substantial uncertainty as to the status of the fishery in relation to the RP chosen.

21. The 1987 Advisory Committee on Fishery Management (ACFM) report to ICES for 1987 (ICES 1988) noted that "biological reference points are intended to provide guidance concerning management, and that no biological reference point can serve as a universal target". For straddling and highly migratory stocks which present particular difficulties for data gathering and fishery management, this less optimistic view now seems in order. It is important to agree on a 'red area' where the continuity of resource production is in danger, and immediate action is needed (such as fishing effort/mortality being significantly reduced), or in the extreme case, that the fishery be temporarily shut down. Here we may refer to threshold management policies (e.g. Quinn et al. 1990), or (to avoid confusion with the acronym TRP), to Limit Reference Points (LRP's). These either correspond to some minimum condition (e.g. a dangerously low spawning biomass) or some maximum condition (a high rate of decline in stock size, or increased mortality rate) at which point an emergency management response (negotiated earlier by the participants in the fishery), is automatically triggered. The use of F_{MSY} as a TRP for management, has more often been supplanted recently by its use as an LRP, because it seems generally agreed that exceeding F_{MSY} has undesirable consequences. Annex I includes a simple calculation demonstrating how this change in emphasis may result in

radically different targets for management if F_{MSY} is viewed as an LRP rather than an TRP.

22. A third group of criteria, qualitative or semi-quantitative in nature, can be incorporated within a "Set of Rules" which determine how the fishery is to be managed. These may specify the management response to, for example, a high discard rate of protected species. Again, if one or more of these rules are broken, it can result in a prenegotiated management response coming automatically into play. One example might be the temporary ban on fishing by a given fleet in a prespecified area when discards or by-catch limits have been exceeded. Another might be triggered if the proportion of immature fish in the catch rose above an agreed minimum. Some Precautionary Approaches may often attempt to act by reference to LRPs or "Sets of Rules" (see accompanying FAO paper on the application of the Precautionary Approach to fisheries).

III. TARGET REFERENCE POINTS (TRPs)

23. **In this section we will be discussing reference points used as targets for fisheries management, implying that they are considered a desirable state of the fishery.**

Choosing the model

24. Reference points are usually derived from a particular biometric or econometric mathematical model. The models underlying the MSY point (and many of the other reference points described later) were originally equilibrium models, which imply that the points on the curve represent the yield that would result from a given standard effort applied for the years necessary for equilibrium to be reached (the 'return time'; Beddington and May 1977). In other words (Hilborn 1979), it is erroneous to assume that a given level of fishing effort/mortality allows a certain surplus yield to be maintained indefinitely, irrespective of environmental conditions. The concept of 'surplus yield'[2] embodies the idea that any shortfall of national harvests below MSY within an EEZ, can be considered 'surplus to the needs' of the coastal State.

25. Due to dramatic improvements in fishing and communications technology, fleet fishing power can be exerted ever more rapidly, and moved from one fishery to another within short time periods. The RP level f_{MSY} for a stock, which in the 1950s could take half a decade or so to reach, can now be achieved in the first year of a new fishery. One point of view (Hilborn 1979) holds that unless there are good statistics for the early years of the fishery when effort is low, it will be extremely difficult to arrive at reliable estimates of the current status quo.

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[2] This interpretation of 'surplus yield 'has found little favour with many coastal States, since catching this surplus negatively impacts catch rates of vessels already in the fishery. A number have concluded that RPs based on fishing rates significantly below F_{MSY} are more favourable economically and ecologically to their fishing industry and resources.

26. Under circumstances of high initial catch rates, a wide overshoot of equilibrium f_{MSY} conditions is inevitable, with associated ecological changes, and there are serious economic problems in revising effort downwards, and adjusting to a much lower equilibrium MSY level in later years.

27. As a result of the above considerations, the use of production models, and particularly models that assume equilibrium in forecasting short-term yield, has been seriously criticised (e.g. Hilborn and Walters 1992). The problems of making decisions under conditions of both uncertainty of the data, and variations in environmental conditions and spawning success, has led management of many fisheries to be based on analytical models. Here, the catch data is supplemented by biological sampling, and ideally by regular surveys of the fish populations, but the problem of achieving a moderately high precision in our knowledge of the status quo has not been solved (see Table 1), and there is still the tendency to refer the fishery to RPs derived from equilibrium considerations, which may be acceptable for the use of RPs for long-term strategic planning. However, establishing if an RP is being met in a given year will need to be based on our best estimate of the current dynamics of the fishery. These considerations are addressed later in this paper under questions related to risk and uncertainty.

The Maximum Sustainable Yield Criterion, F_{MSY}

28. The 1982 Convention specifies only one technical reference point, notably, the Maximum Sustainable Yield (MSY), as a descriptive term for the highest point of the curve traced between the annual standard fishing effort applied by all fleets, and the yield that should result if that effort level were maintained until equilibrium is reached. This is at first sight an obvious target for management of a single species fishery, and it was widely used for this purpose by fishery commissions in the 1960s and 1970s. Subsequent developments in the theory and practical experience in fishery management have cast doubts on it as a safe TRP, and this sparked the search for alternative reference points, as summarized below:

29. The MSY, and its equivalent levels of standard fishing effort/fishing mortality (f_{MSY}/F_{MSY}), was formulated first for the symmetrical Schaefer or logistic model (e.g. Fig 2). The concept was 'model based', depending on one of the several production model formulations now in the literature (e.g. Pella and Tomlinson 1969), and requires statistical fitting of historical catch and standard effort data. The effort level at which the f_{MSY} catch occurs can be converted to a fishing mortality F_{MSY} if the constant of proportionality q is known. Choosing F_{MSY}, or any other reference point, implies that the underlying mathematical model of fish population dynamics is (at least implicitly) agreed on in choosing this TRP. The question may however be less one of picking the reference point with the most robust theoretical underpinnings, but picking one that provides conservative advice under conditions of uncertainty, and from this perspective, the MSY level has not performed well (see e.g. Doubleday 1976, Larkin 1977, Sissenwine 1978, Garcia 1984). The main criticisms of the MSY as a TRP are the following:

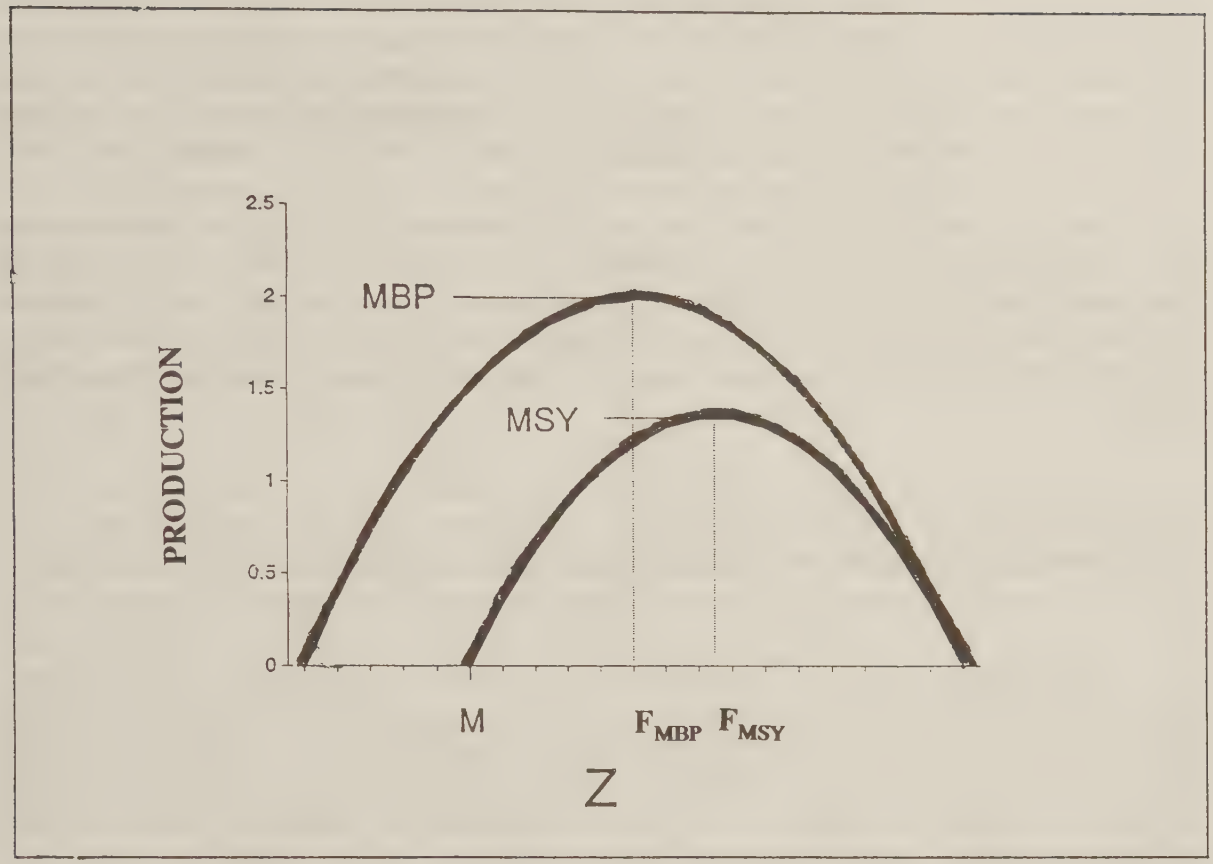

Fig 2: Illustrating for the equilibrium Schaefer model, the relationship between MSY, Z, and the Fishing rate corresponding to the Maximum Biological Production (MBP) for a stock (for which $F_{MBP}<F_{MSY}$).

30. Few explicit estimates have been possible of the accuracy with which MSY conditions have been reached, but inspection of many production models suggests that an accuracy of better than ± 20% of the standard effort yielding MSY would be unusual. The MSY is obtained by statistical fitting of the model to historical data, and implies that what happened in the past has a similar probability of occurring in the future. However, in a series of years with very poor recruitment, a fishing mortality F_{MSY} produces a yield well below that from fitting the past data series. Attempting to harvest the statistically obtained MSY in these years would require fishing above, and possibly well above, F_{MSY}. For this reason, the use of the word 'sustainable' for an MSY obtained in the conventional way has been criticized, since as noted by Doubleday (1976), "in the presence of fluctuations in production, attempts to remove the MSY yield each year from a stock leads to disaster".

31. Given the uncertainty as to the actual status quo with respect to this RP, a fishery believed to be operating in the region of F_{MSY} is for 50% of the time either overfishing or underfishing with respect to this benchmark. The biological responses of the resource to overfishing or underfishing are not necessarily symmetrical: overfishing leads to fewer age groups in the fishery, hence increasing the contribution of occasional good years classes to the overall yield, as well as leading to declining mean sizes and catch rates. Relatively constant year-to-year recruitment is the exception rather than the rule (e.g. Hennemuth et al. 1980), but reduced or less regular recruitment with declining spawning stock size is accompanied by increased dependence for stock replenishment on newly-maturing age classes. Increased variations in abundance due to a greater influence of environmental changes on the stock size lead to increasingly heavy reliance on research data, especially if catch quotas are the preferred management measure. From theoretical considerations, Beddington and May (1977) noted that simply aiming at a TRP without feed-back control policies will not be effective. They predicted that fluctuations will become more severe, and the return time of the population to equilibrium will markedly increase once f_{MSY} has been exceeded.

32. The uncertainty as to which type of production model is appropriate for a particular fishery can only be resolved when overfishing has occurred and the total effort that provides MSY has been exceeded. Catches may then drop (implying a dome shaped model), or reach a plateau (as is often the case in tropical shrimp fisheries).

33. Effort overshoots of the f_{MSY} target are an almost inevitable feature of open access fisheries, so that the type of model to use, and the level of effort or fishing mortality which approximately corresponds to MSY, under the best of circumstances may be only roughly relatively well known, allowing other TRP benchmarks (e.g. $2/3f_{MSY}$:Doubleday 1976) to be defined in relation to it. 'Controlled overfishing' strategies have even been proposed as one way of better locating MSY conditions and, as noted above, often occur despite a stated objective of MSY management. They are dangerous however and difficult to reverse: surplus fishing vessels, once established in a fishery, may be difficult to displace, given current shortages of alternative opportunities, and a loss in economic yield will certainly occur.

34. The effects of heavy fishing in reducing stock size can lead to a species losing its competitive advantage as its ecological niche is occupied by some other species with a similar trophic 'footprint'. The probability that the ecosystem will move to an alternative ecological configuration seems to increase as effort goes beyond f_{MSY}.

35. Sissenwine (1978) has pointed out that there is often an erroneous identification of MSY for little-studied stocks with the Maximum Average Yield (MAY). (This latter quantity has occasionally been used as an RP, but gives dangerous weight to the early years of the fishery when the virgin stock was being fished down). Sissenwine (1978) also noted that a literal interpretation of MSY for a stock subject to wide variations in recruitment, would be that level of catch which could be removed in perpetuity from the resource with a low probability of endangering it under these conditions. This interpretation is radically different, requires a different notation from MSY as normally derived, and this RP is referred to here as MCY (the maximum constant yield), since it

implies much lower levels of fishing mortality (F_{MCY}), and very much lower catches than at F_{MSY}. Such a new definition could however provide a useful TRP for stock rebuilding, and could be estimated from simulation if some information were available on the likely variance of annual recruitment.

36. Following the Marginal Yield concept of Gulland, Doubleday (1976) postulated that fishing at the effort level that corresponded to two thirds of the effort needed to produce MSY would yield a very large fraction (80% or so) of the overall yield at MSY, with a reduced risk of stock collapse. This empirical measure, although safer than $f_{MSY,}$ like $F_{0.1}$ (see later), has been criticized as empirical and insensitive to changes in recruitment. It may be useful to note (Table 2) that this approach to setting reference levels for F may be generalized for commonly used population models. This table illustrates for a commonly-used model that reducing effort levels below those yielding MSY does not result in a correspondingly large reduction in the long-term equilibrium yield once the stock (and the catch rate) have recovered from the effects of the previously heavier exploitation rate.

Table 2: Assuming a Schaefer model at equilibrium, the table provides yield values (as percentages of MSY), for different percentages of the fishing effort (mortality) rate, F_{MSY}. (CPUE = equilibrium catch rate)

% of F_{MSY}	10	20	30	40	50	60	70	80	90
% of MSY	19	36	51	64	75	84	91	96	99
% of CPUE at MSY	+190	+180	+170	+160	+150	+140	+130	+120	+110

37. Reference points derived from production models, such as MSY, suffer from difficulties of population analysis if the competing fleets exploiting a resource do not exploit the same age groups in the stock. Under these conditions some form of analytical approach is necessary. The first of these analytical RPs defined was F_{MAX}.

The Maximum Yield Per Recruit criterion, F_{MAX}

38. The theory of population dynamics places early emphasis on the calculation of that level of fishing mortality for a given size at first capture, which maximizes the yield from a fixed number of recruits with fixed growth and natural mortality schedules entering a fishery, with a known vulnerability to fishing. This was one of the earliest benchmarks for fisheries management and, as for MSY, suffered from a number of failures as a TRP. A theoretical criticism is that it does not take into account the effect of fishing at F_{MAX}

on the number of adults left in the population and hence its reproductive potential. Although generalizing about the differences between bench marks developed from production modelling and analytical models can be hazardous, there seems little doubt (e.g. Clarke 1991) that this reference point is usually to the right of F_{MSY}, and that fishing at this rate over a period of time is liable to deplete the spawning stock and reduce future recruitment. Although there may be good reasons for retiring F_{MAX} as a TRP, it could be a possible upper limit or LRP.

The marginal yield criterion, $F_{0.1}$

39. For a number of species there is no clear maximum to the curve of yield per recruit against F, and the $F_{0.1}$ point proposed by Gulland and Boerema (1973) does not require this, being an arbitrary criterion based on the slope of the yield per recruit curve. $F_{0.1}$ is the fishing mortality rate at which the slope of the yield per recruit curve as a function of fishing mortality is 10% of its value at the origin (Fig 3). In proposing this TRP as a safe point on the trajectory of decreasing yield per recruit as F_{MAX} is approached, Gulland and Boerema (1973) noted that there was not at that time a single theoretical model for setting annual catch quotas that combines the desirable features of being readily understandable to decision-makers, describing and realistically predicting to an acceptable degree of precision the events within the fish stock, and being capable of application to a specific fishery without great demands in data and analysis. It is not clear that the situation is greatly improved today, at least for high seas fisheries.

40. The $F_{0.1}$ measure, although arbitrary, is in a sense, a bioeconomic criterion, in that a marginal yield of less than 10% was felt to be close to the point at which most fisheries administrators would consider further increases in fishing mortality or effort to be no longer economically worthwhile. This measure has been widely used in many fisheries of the Northwest Atlantic. F-based strategies have been followed off eastern Canada for more than a decade, and $F_{0.1}$ is often used in establishing overall quotas. Declaration of the correct and unbiased catch data is essential to estimating current F-values under quota control, but there has been a gradual erosion of the accuracy of commercial catch reporting. This has affected scientific assessments, and has been especially pronounced where fleet overcapacity is a problem. As a result there is a high probability that target F values would be exceeded. This, and not just the changes in $F_{0.1}$ that occur with changing fishing pattern, and input values for M (Jakobsen 1992), may be the main explanation for declines in several stocks managed under $F_{0.1}$ criteria. A more serious problem in using this TRP for straddling and highly migratory stocks is how to calculate a value for $F_{0.1}$ if fleet-specific vectors of F-at-age for an exploited resource within different jurisdictions are quite different, and their relative efforts change from year to year.

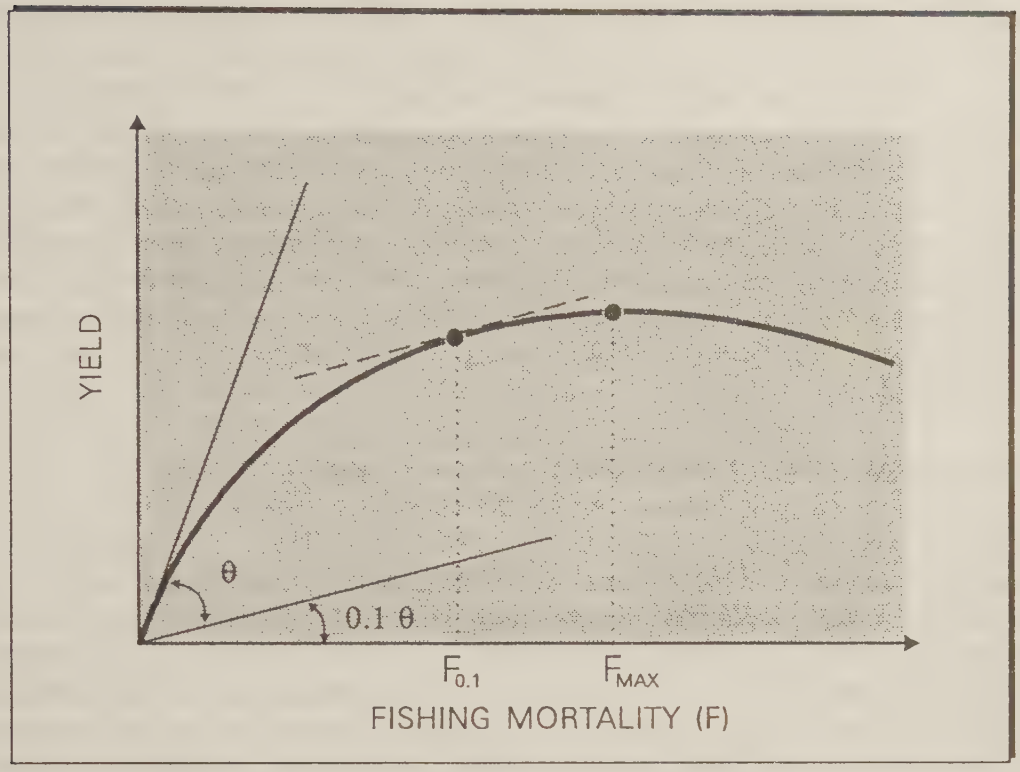

Fig 3: Illustrating the method of defining $F_{0.1}$, given a known relationship between fishing mortality rate and yield (or more strictly, yield/recruit), as the tangent to the curve for a straight line with a slope 1/10 of the initial rate of increase in Y/R.

Reference points based on the Natural Mortality Rate, M

41. New fisheries usually develop in the absence of adequate assessment information, and management has to proceed on the basis of information available at that point in time. It is important that the rate of fishing during the early stages does not exceed the rate of learning (e.g. Hilborn and Sibert 1988). A more cautious approach may result in underexploitation, but this will not necessarily lead to a loss of potential yield (see later sections on Risk). In the 1960-70s, many new fisheries developed in different parts of the world, for which the only data on stock status was one or several estimates of biomass from exploratory fishing campaigns or fishery surveys. In an attempt to provide some basis for fleet and fishery development, a simple empirical formula for the MSY was proposed by Gulland (1973) in terms of the virgin biomass B_0 and the natural mortality rate M, notably $MSY = 0.5MB_0$. (A reformulation of the second yield equation in Annex I), and follows the symmetrical Schaefer yield model in assuming that MSY will occur at half the virgin stock size B_0, and that at MSY, the fishing mortality and natural mortality rates will be equal. Later, a more cautious approach was used, and Gulland generalized the equation to $MSY = x.M.B_0$ with the value of x being related to the stock characteristics. Garcia et al. (1989) proposed several estimators for MSY when historical data series are not available.

42. There is in fact little empirical evidence that $F_{MSY} = M$ for a majority of stocks. Beddington and Cooke (1983) suggested that x is generally smaller than 0.5, while for tropical penaeids Garcia and Lereste (1981) suggested that values x = 0.32 to 0.44 are appropriate. From a limited set of 11 stocks, Caddy and Csirke (1983) found values were bounded by x = 0.33 to at least x = 4, the lowest values being shown by short-lived shrimp and a sardine populations, and the highest by two northern demersal finfish; apical predators with low natural mortality rates. From an analysis of a series of small pelagic stocks, Patterson (1992) found that only low exploitation rates (no more than 40%) corresponding to not more than x = 0.33 are sustainable. The point of mentioning these very approximate benchmarks is that for many straddling stocks off developing coastal countries, setting 'Precautionary' RPs might still have to draw upon such procedures.

The overall mortality rate at Maximum Biological Production, Z_{MBP}

43. Production model theory begins with the idea that virgin populations are dominated by large, old individuals, whose contribution to biological production (growth, yield plus deaths due to predation) is lower than when younger individuals dominate the population. We can postulate the existence of a mortality level Z_{MBP} at which the biological production from the stock is maximal, and this is shown for the Schaefer model in Fig 2. Recognizing that 'dissecting' the overall mortality into components due to fishing, predation, etc. is often problematical, there may be advantages in expressing reference points in terms of the overall mortality Z experienced by the stock due to all causes of death. Caddy and Csirke (1983) provided measures of Z_{MBP} and F_{MBP} for the Schaefer model, where this index corresponds to a fishing mortality consistently below F_{MSY}, being progressively more so for species low in the food chain with high natural mortality rates. Die and Caddy (in press) showed that it is difficult to produce excessively high fishing mortalities using this TRP. There should be less risk of ecological perturbation when the stock is at its maximum productive capacity.

TRPs derived from stock-recruitment considerations

44. Measures that aim at conserving the spawning stock are often defined in terms of the minimum biomass (of spawners) that is believed to yield the highest number of young recruits. The capacity of most fish stocks to reproduce themselves has been shown to be influenced by the spawning stock size, for most if not all stocks studied, the biomass corresponding to the greatest surplus of recruits over spawning stock size. The spawning biomass corresponding to the Maximum Surplus Reproduction (Ricker 1975), occurs at some level intermediate between a high and a very low stock size (Fig 4). In theory, there is for each stock size above the level of Maximum Surplus Reproduction, a level of fishing mortality in each year, F_{MSR}, that would result in this 'best' stock size surviving for reproduction in that year. In practice, however, given naturally-varying stock sizes from year to year, this level of fishing mortality would have to be changed annually to achieve a 'Constant Escapement' (see later). Thus, not only the total landings, but the fishing rate would also need to be tuned annually, in order that the same biomass of spawners survives. This may be a realistic strategy for managing runs of salmon counted through a fish weir in a river each year, but is likely to exceed the probable information

levels for the stocks in question here. A further problem is, of course, in defining the correct model to use under conditions of high variability of survival to recruitment even at the same spawning stock size.

45. Due to heavy fishing and depressed stocks, fishery scientists in the North Atlantic have moved in recent years to emphasizing spawning stock considerations in advice to management bodies. This has been phrased in terms of spawning stock biomass or biomass per recruit ratios referred to the reproductive potential under virgin stock conditions. This has led to increased research in recent years on the density dependent processes that underlie fishery dynamics. These density dependent processes have revealed that the number of recruits increases as adult populations grow from very small sizes, but for many resources the number drops at a high adult population size, due to individual competition for food, space and spawning sites.

46. Clarke (1991) carried out simulations that showed that for northern demersal stocks a yield of at least 75% of MSY is possible as long as the spawning biomass is maintained anywhere in the range 20-60% of the unfished level, irrespective of the spawner-recruit relationship. A relative spawning biomass in this range can be achieved by choosing an F value that will reduce spawning biomass per recruit to about 35% of the unfished level. The equivalent F reference point is usually very close to $F_{0.1}$. The relationship between spawning stock size and number of recruits is of key importance to the decisions made on RPs, but a long time span of annual data on adult population size and recruitment under a wide range of population sizes are needed to produce a reliable stock-recruit curve. This is rarely available for setting RPs for lesser-studied stocks.

47. The use of reproductively-based TRPs has been pioneered in the ICES area (e.g., ICES 1984), based on plots of recruitment on spawning stock biomass (Fig 5). Three arbitrary criteria have been proposed, one of which, F_{MED}, has the characteristics of a TRP and corresponds to the fishing mortality when increases in stock size due to recruitment in half of the year have more than balanced losses due to mortality. Two other benchmarks (F_{LOW} and F_{HIGH}) bracket F_{MED}, are similarly defined to leave 90% and 10% of the data points for recruitment above the line through the origin corresponding to that level of fishing mortality (Fig 5), and have the following properties (ICES 1991; Jakobsen 1992):

F_{LOW} : a low probability of stock decline, and some likelihood of stock increase
F_{MED} : likely that current stock levels will be sustained
F_{HIGH}: likely that fishing at this level will result in stock declines

48. All of these measures appear less susceptible to assuming an incorrect value of M than F_{MAX} and $F_{0.1}$ levels (Jakobsen 1992). Sissenwine and Shepherd (1987) proposed a similar benchmark, F_{MED}, the fishing mortality rate at which, on average, each year class replaces the spawning biomass of its parents so that the population fluctuates without trend. This measure which is independent of the form of the stock recruitment relationship, fell close to F_{MAX} and F_{MSY} for Georges Bank haddock.

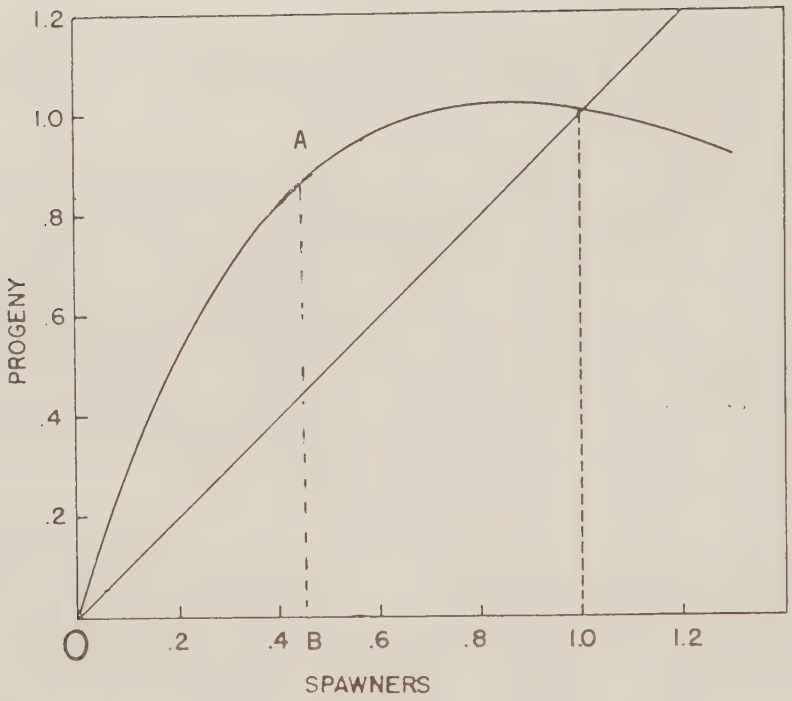

Fig 4: Illustrating (after Ricker 1975) a generalized relationship between spawning stock size and number of recruits (progeny). The line A-B corresponds to the stock size or biomass of spawners for this specific relationship where the surplus of progeny over parental stock size is maximized: the point at Maximum Surplus Reproduction.

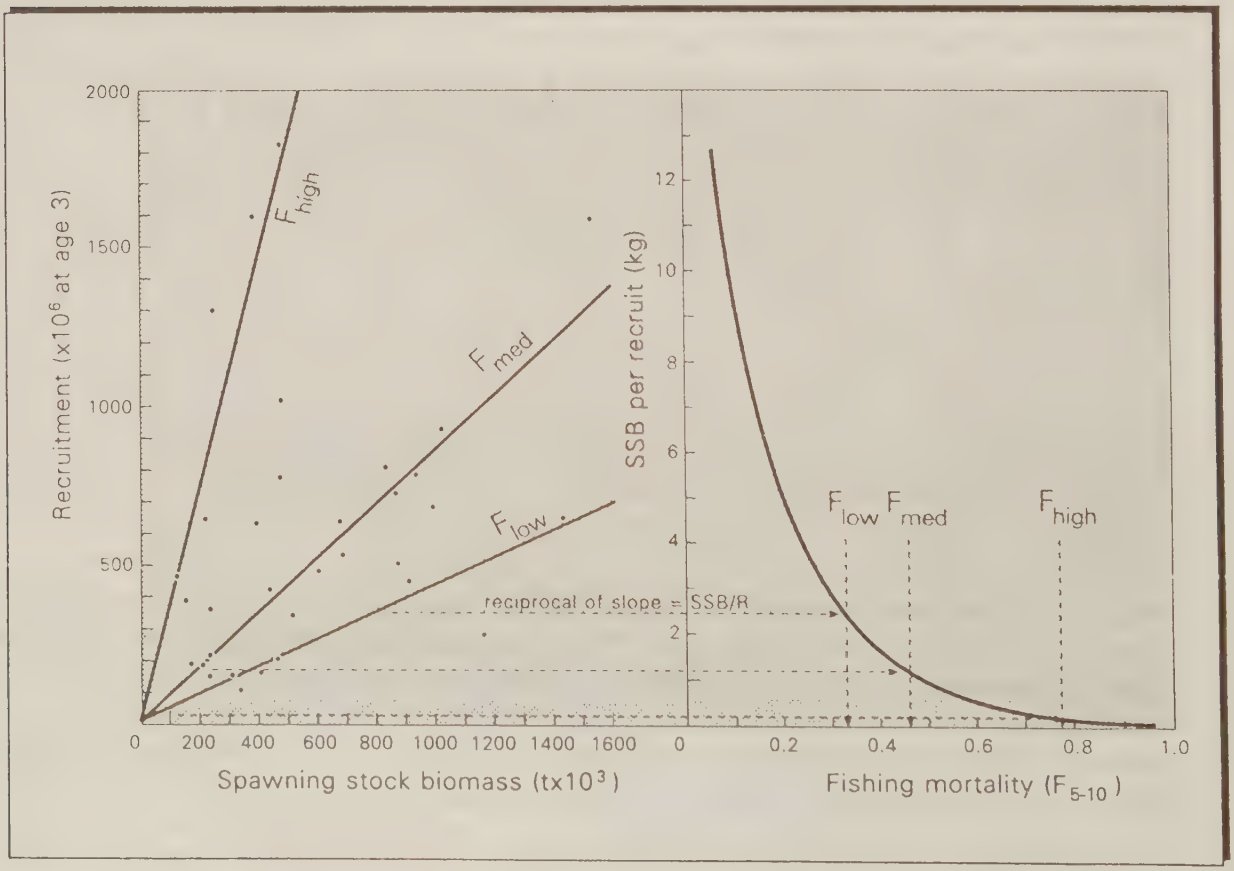

Fig 5: Illustrating the definition of F_{LOW}, F_{MED} and F_{HIGH} in the case of the North-East Arctic Cod stock (redrawn from Jakobsen 1992).

49. Calculations of the 'spawning stock biomass per recruit' can be carried out in a similar way to yield/recruit calculations if information on maturity/fecundity at size or age is available, even if the stock-recruit relationship is unknown. These calculations are usually expressed as a percentage of the spawning stock biomass per recruit under unfished conditions (%SSB/R). In a recent comparative study, %SSB/R was found to be positively correlated with natural mortality and negatively correlated with various indexes of size; thus cod and most flatfish support low levels of %SSB/R, but some pelagics require values as high as 40-60% for consistent stock replacement. Although these conclusions agree with those in the earlier section on M reference points, it is probably dangerous to widely extrapolate them outside their region of origin, since the detailed data sets this generalization is based upon are mainly restricted to fishery resources in higher latitudes. Nonetheless, the use of %SBSB/R criteria is not as information-demanding as other reproductive criteria, and has potential in the present context.

TRPs derived from economic considerations - the optimal fishing effort, f_{MEY}

50. The normal workings of the market are believed to maximize economic benefits to participants (Gordon 1954), but in open access ocean fisheries, the institutional framework does not ensure that the individual efforts of private agents (fishermen), working to improve their individual economic situation, will 'guide the net sum of private activities towards the common good'. In fact, recent analyses of global fishery trends (FAO 1992 a.b) have revealed a general state of overexploitation of many world fishery resources, and that the high level of over-investment in fleets is the major causal factor for overfishing within and outside EEZs. Combined with restrictions on fisheries within EEZs, this has been a motive force for movement into largely unrestricted fisheries beyond 200 miles. The global sum of fishing subsidies was estimated in FAO (1992b) at some US$ 54 000 million per year. The development of effective management criteria, therefore, would potentially release substantial global financial resources, as well as reducing adverse impacts on stocks.

51. An extensive literature on fisheries economic theory has developed in which the Gordon-Schaefer equilibrium production model (Gordon 1954; Schaefer 1957, Clark 1976) plays a central part. This theory is summarized briefly in Fig 6, which shows that there is an economic TRP, the effort level yielding the greatest rent from the resource, and that for a linear cost curve, this inevitably occurs to the left of f_{MSY} on the fishing effort axis, as for $F_{0.1}$ and F_{MBP}. The effort level f_{MEY} as a TRP, is responsive to changes in the economic environment, such as the market price of fish, interest rates, and the costs of fishing, and is not independent of changes in fish abundance. For example, if the market price is independent of the availability of other similar resources of the same type (i.e., it is not a 'price taker' from some larger global market, as is the case for tuna, salmon and shrimp), its market price may increase with declining abundance such that the point f_{MEY} could be displaced towards a higher level of effort. Subsidies and other socioeconomic considerations, such as taxes on fuel, will also have an overriding influence on an economic RP (see e.g., Panayotou 1988), although economic considerations obviously should play an overriding role in national decisions to participate in a fishery. Perhaps one further reason why such economic reference points

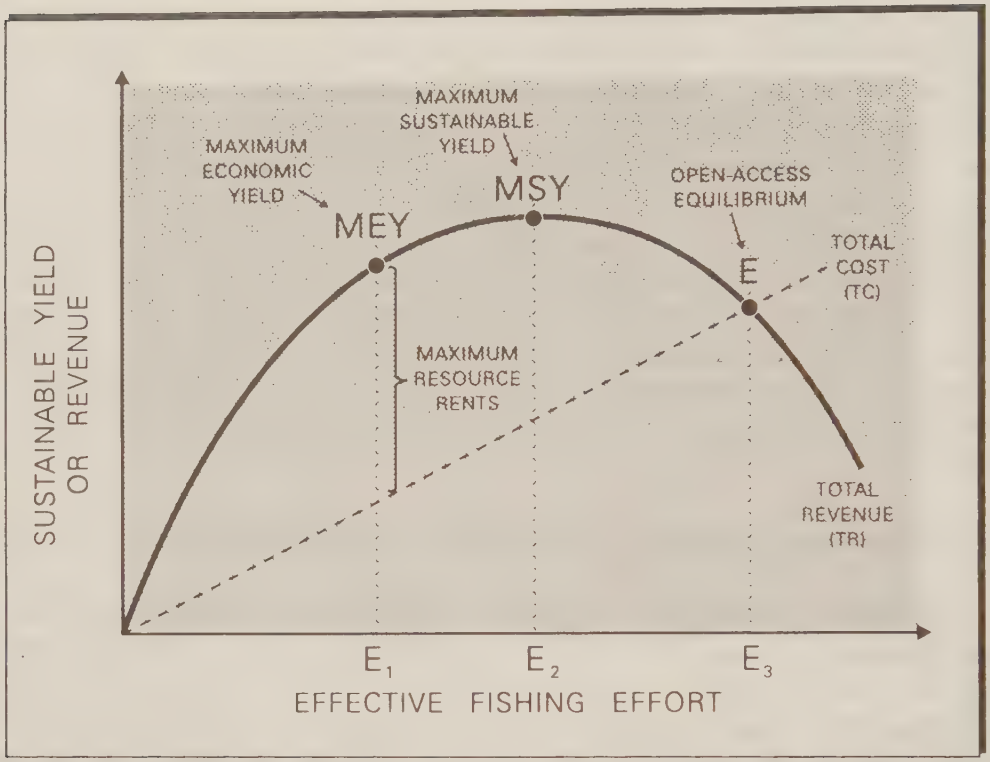

Fig 6: The Graham-Schaefer equilibrium production curve relating yield or revenue to effective fishing effort, and showing three Reference Points: MEY, MSY and the bionomic equilibrium point E; these occur at progressively higher levels of fishing effort.

may not be practical as reference points for management of straddling stocks (and even less so for highly migratory resources), is that each national fleet may have a different economic optima, depending on its costs, earnings and national market prices. In practice, f_{MEY} is not easily defined in most fisheries involving fleet components with different gears and fishing practices, and this is the case for fisheries on many straddling and highly migratory stocks, although a fishery which generates rent is not necessarily free from adverse impacts on the stock. Since f_{MEY} occurs at lower levels of effort than f_{MSY}, fisheries operating directly or indirectly in relation to this economic benchmark have less chance of ecological impacts than at f_{MSY}.

52. Given the largely insurmountable difficulties in fisheries management in the absence of industry compliance (due to misreporting, or lack of cooperation in data gathering), it may be mentioned here that reference points (particularly involving socio-economic considerations) are only likely to be respected if decided upon in cooperation with the fishing industries concerned. Under current conditions when the world shortfall in fish resources is becoming apparent (FAO 1992a), the clear advantages of stock rebuilding strategies should be apparent to the industries concerned.

IV. LIMIT REFERENCE POINTS (LRPs) FOR FISHERY MANAGEMENT

53. In this section will be discussed threshold or limit reference points that are not targets for management, but can serve as indicators of an undesirable stock status when management action is urgently needed. Implicit to the use of an LRP is that negotiation between the parties concerned in the fishery pre-establishes the response to be taken automatically once the fishery assessments indicate that a 'red zone' is being approached or has been entered, where pre-agreed long term conservation objectives are endangered.

F_{MSY} as an LRP

54. In Annex II a simple calculation illustrates that using F_{MSY} as an LRP rather than a TRP could provide flexibility in choosing a more cautious F-based TRP that has useful management characteristics. It is important to have an estimate of the likely range within which the current fishing mortality (F_{NOW}) is known. While few such estimates are available in the literature, it seems unlikely for well studied fisheries that its standard deviation is less than 15-30% of the current F value, and for poorly studied fisheries where few estimates of the error in F_{NOW} have been made, much higher. In the table in Annex II, an LRP of $F_{MSY} = 0.6$ is assumed, and it is suggested that if, for a well-studied fishery, the standard deviation of F_{NOW} is only a quarter of its expected value, then it would be unwise to aim for a TRP of more than $F = 0.53$ (89% of F_{MSY}) if management does not wish F_{MSY} to be exceeded more than 30% of the time. If, on the other hand, one standard deviation above F_{NOW} could be double the expected value, then fishing at beyond a TRP of $F = 0.26$ (43% of F_{MSY}) would be unwise if F_{MSY} were not to be exceeded more than 10% of the time. Obviously these calculations are tentative, but illustrate the great economic importance of appropriate statistical sampling in allowing a higher rate of exploitation for the same level of risk, than where statistical and research mechanisms are poorly developed.

55. A more elaborate use of MSY as an LRP was incorporated into the new management procedure developed by the International Whaling Commission (Garrod and Horwood 1979), where a maximum harvest of 90% of MSY (set at 60% of the unexploited stock level) is agreed to, to be reduced progressively by 10% for each 1% shortfall of the stock below the MSY level, leading to a threshold for entry of the stock to a fully protected category, as soon as stock size drops to 90% of the MSY level. This example also illustrates one other essential feature of an LRP-based management system, the pre-negotiation of future automatic management responses once the system enters an agreed endangered state.

LRPs derived from stock recruitment considerations

56. As noted, scientific attention has focused recently on the definition of LRPs which signal a dangerous situation of reduced probability of future recruitment to the fishery, and practical management advice has been recommended on the basis of a safe minimum spawning stock size, or on an F level that provides that is believed to be a safe limit for Spawning Stock biomass/recruit, expressed as a percentage of that calculated for the virgin stock (%SSB/R). Thus, Hall et al. (1988) and Quinn et al. (1990) both

suggested to fish at some fixed rate so long as the spawning biomass remains above a pre-defined threshold size, but to suspend fishing when demersal fish stocks drop below this level. One specific criterion that falls into this category, as mentioned, would be the F_{HIGH} point of Sissenwine and Shepherd (1987), since above this point there is little evidence that the stock can produce enough recruits to sustain itself. In the ICES area (ICES 1991) the stock biomass below which "the probability of a poor recruitment increases as spawning stock decreases" is referred to as the Minimum Biologically Acceptable Level (MBAL), and is presumably intended for use as an LRP.

57. In the United States, fisheries are managed through management plans which require operational definitions of overfishing based on a maximum fishing mortality rate, minimum stock biomass or other appropriate biological reference points. In Anon (1991) P.M. Mace and M.P. Sissenwine note that 60% percent of these definitions to date have been based on spawning stock biomass/recruit (SSB/R) analysis, with typical values ranging from 20-35% of virgin stock levels. A survey of 91 spawner recruit data sets for Europe and North America suggest that the replacement %SSB/R (i.e. the fishing strategy which, on average, replaces the spawning stock) varies considerably between taxonomic groups, but averages 20% overall. Given the relative depletion of many of these stocks, it is possible that these levels should be regarded as LRPs rather than TRPs.

LRPs as 'Sets of Rules'

58. As noted, LRPs can be incorporated into a set of management criteria, which if one or more are infringed, triggers a preset management response. One such set of constraints has apparently been developed for the Eastern Bering Sea/Gulf of Alaska groundfish fishery and includes: (a) a threshold biomass set at 20% of the virgin stock biomass; (b) a maximum fishing mortality rate set at 30% of the relative %SSB/R; and (c) a maximum fishing mortality rate set at 80% of the M value for the species concerned. Die and Caddy (in press) suggest other possible warning signals; (d) when total mortality Z rises above that corresponding to Z_{MBP} or Z^* for the stock (see paragraph 61; (e) when the mean size caught falls below the mean size at first maturity, or when the proportion of mature individuals in the stock falls below some agreed percentage of that for the virgin stock; and (f) when annual recruitment remains poor for a predetermined number of years in a row. Other robust indices which are often associated with low stock size and hence reduced intraspecific competition, are increases in weight-at-age and reduced size at maturity (Jakobsen 1990).

59. For short lived species (e.g. some squid resources), sets of rules may be invoked in sequence in the same season. Thus, fleet size and overall effort can be controlled to aim for a target level of 'escapement to spawning' as an agreed percentage of that calculated for the same number of recruits with no fishing. This level can be fine-tuned later in the season if a real-time measure of accumulated catches is maintained, and when on-going surveys of abundance/availability allow real-time changes in the abundance of pre-spawning individuals to be monitored.

RPs based on measures of the size at capture

60. In assessing the effects of size at first capture on the yield per recruit from a stock, an optimum size at first capture that provides the maximum yield per recruit can be calculated for a given set of population parameters and a particular level of fishing mortality. In the case of straddling stocks and hignly migratory species however (Caddy 1982), it is not always possible for this optimal size at first capture to be maintained throughout the range of the unit stock, since different age groups may have different distributions or availabilities within the jurisdictions the stock range is divided into, and maintaining a single optimal size at first capture would only be possible if arrangements are made for all harvesting to be carried out in seasons and jurisdictions where the optimal sizes are available (Fig 7).

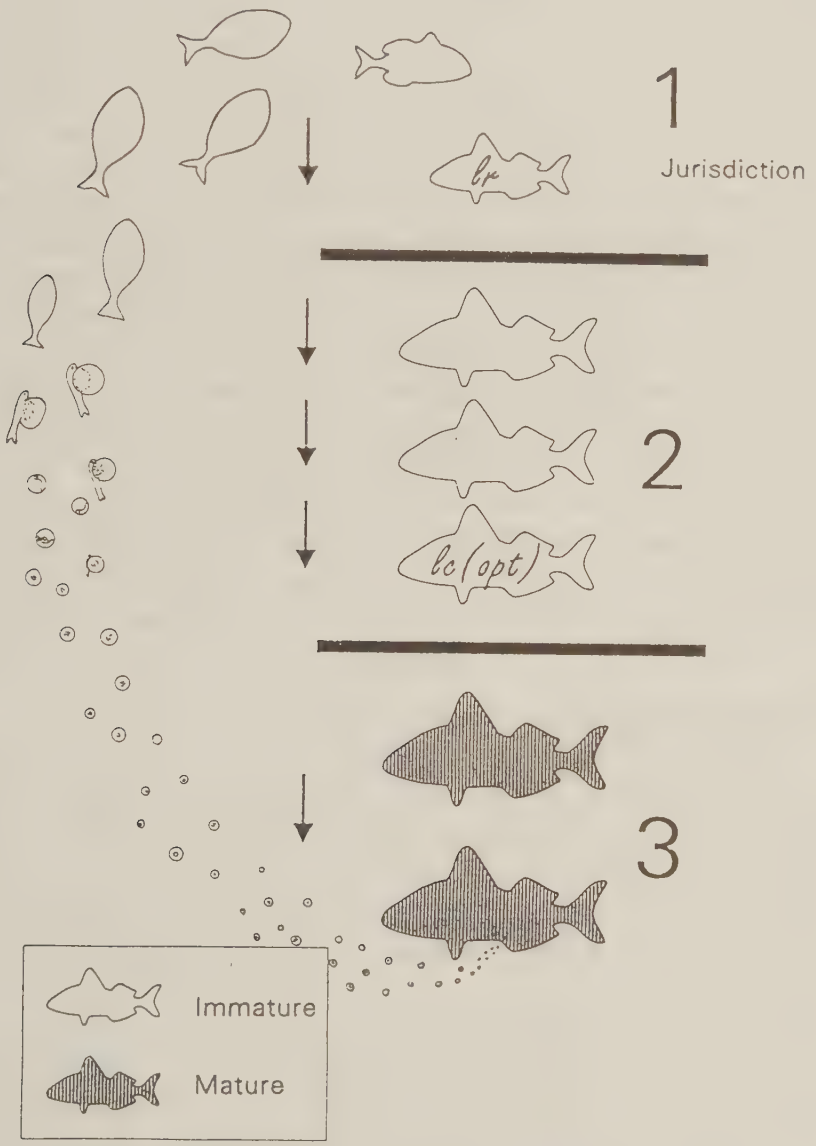

Fig 7: An idealized gauntlet fishery for a highly migratory species crossing 3 jurisdictions during its life history. The age at first availability to capture t_c , occurs in jurisdiction 1; the optimum size at first capture (lc_{opt}) yielding maximum Y/R in jurisdiction 2, and spawning in jurisdiction 3.

61. The problem of controlling overexploitation is, of course, most pronounced when the age at first capture falls below the age at first maturity and there is a high risk of recruitment overfishing. If control of fishing effort is unreliable, one reference point would be to require fishing to only take individuals at a size at and above that at first maturity without discarding and damage to undersized individuals. There may be an advantage in cases where M is not precisely known of basing biological reference points on the overall mortality experienced by the stock. A more practical biological criterion was proposed by Die and Caddy (in press), namely, the limiting overall mortality rate Z* when the mean size in the catch equals the mean size at first maturity. Evidently the use of this type of RP requires consideration of the selectivity of the gears in question.

LRPs derived from economic considerations

62. It seems generally acknowledged (e.g. Panayotou 1988) that one LRP on the curve of revenue plotted against fishing effort, although extremely undesirable, is an 'attractor' for an open access fishery, namely the point of 'bionomic equilibrium' (Gordon 1954) where net earnings from the fishery equal the costs of fishing. Although beyond this point the fishery is operating at a loss, the effort level corresponding to this point (E in Fig 6), can in fact be exceeded (see FAO 1992b), especially when subsidies reduce the cost of fishing. Since catch rate (Catch Per Unit of Effort: CPUE = q.B) is often assumed proportional to biomass, the catch rate or CPUE per standard fishing day is one LRP criterion employed, particularly in some fisheries for highly migratory resources where survey methods are difficult to implement. A useful economic LRP is the minimum CPUE which yields daily earnings per cost of fishing at which the fleet extracts zero rent. It is presumably axiomatic that a fishing operation that does not generate rent but contributes to dangerously depleting the stock is difficult to justify. One possible economic measure that could be applied internally by participating countries in a fishery on straddling or highly migratory stocks, would be to require participants to demonstrate that they are extracting a net rent by their activities.

V. SPECIAL CONSIDERATIONS

Reference points for highly migratory resources

63. The Reference Points mentioned earlier for management of single stocks have different degrees of applicability for highly migratory resources, although the specific life history characteristics of these resources argue more strongly against exclusive reliance on dynamic pool models as a sufficient response to the needs of management and conservation. As noted in FAO (1993a), sophisticated management arrangements may be needed to deal with sequential fisheries. Although occurring to a lesser extent for some straddling stocks, it is typical of highly migratory resources that multiple fisheries occur at different loci on the overall migratory route. Such local fisheries are often seasonal, and often too short to allow declines in catch rate with time and size to be unambiguously attributed to fishing as opposed to migration. Each fishery may exhibit different availabilities to fishing and different age compositions of the catch. Under these circumstances, no ready alternatives seem available other than pooling catch data and performing a global assessment, and then, where possible, moving to define a more

detailed escapement or gauntlet model (Paulik and Greenough 1966) such as implied by Fig 7.

64. One practical consideration that applies to multi-jurisdictional fisheries for a common stock, is that each fishing location may be assessed as favourable or unfavourable in relation to a size-based RP, the optimal size at first capture $l_{c,}$ as judged from Yield per Recruit or Spawner per Recruit analyses for the whole life history. The sacrifices needed either achieve an optimal Yield per Recruit, or to protect the spawning stock or juveniles from overfishing, are not equal for all participants, and often depend on the actions of one or a few coastal States where these critical life history stages are undergone. Under these circumstances, Caddy (1982) noted that the overall yield from the population if all participating States are obliged to harvest the stock exclusively within their areas of jurisdiction, will be suboptimal if only a few (e.g. juvenile) age classes are available in the given EEZ. The optimal solution from a yield per recruit perspective would then be to seek agreement to ban all harvesting except in seasons/areas where the size frequency, catch rates and international market prices are optimal but, of course, to provide a catch quota or other compensation to those parties prepared to renounce fishing suboptimal sizes within their own jurisdiction.

65. In a fishery of the type illustrated in Fig 7, the best overall RP is one ensuring that a certain spawning biomass survives all fisheries to reproduce the stock. From a simple example (Table 3), it is clear that this can be achieved in a variety of ways, which all result in the same agreed cumulative risk of death prior to spawning. If the mechanism proposed in the last paragraph is rejected in favour of sub-optimal harvesting within each jurisdiction, the vector of mortalities-at-age, and the allocations they correspond to, can be decided by negotiation between participants.

Table 3. A hypothetical illustration that two alternative sets of F values at age and their equivalent age/site specific quotas can result in the same RP for survival to maturity. This may have relevance where age classes are migrating through different jurisdictions where different levels of exploitation apply

AGE CLASS	FISHERY-BASED Fs (II)		FISHERY-BASED Fs (II)	
	F (age)	Quota (t)	F (age)	Quota (t)
1 (Immature)	0.2	780	0.45	1,131
2 "	0.2	960	0.21	763
3 "	0.2	861	0.14	580
4 "	0.2	685	0.1	441
5 (Mature)	0.2	513	0.1	365
Survival to maturity at Age 5: (Quota)	13.5%	(3799t)	13.5%	(3,279 t)

Ecosystem considerations and reference points for multispecies fisheries

66. The 1982 Convention (UN 1983) pays attention to the potential impact that fishing one resource may have on others and on the food web as a whole. These kinds of impacts are likely to be most pronounced for species that are competitors, predators, or prey of the target species, or are taken as by-catch. A set of reference points that explicitly recognizes all of these specific types of interactions, and quantifies them, has not been applied, and goes beyond the level of knowledge presently available for almost all marine ecosystems. One praiseworthy attempt to do this is found in the Convention on the Conservation of Antarctic Marine Living Resources (see CCAMLR 1993), but many Antarctic finfish resources, despite the clauses in the Convention, are severely depleted. To a significant extent this is due to a lack of control of access, or means to enforce it. A further comment is that the Convention seems to assume that fishing rather than natural variation is the key causal factor in causing declines in stock size (if not, it will be impossible to prevent a decrease in the size of stock to below that which ensures stable recruitment). In reality, a 'stable recruitment' cannot be ensured by management action, even if stock sizes above MBAL are maintained.

67. Article IIc of the above Convention explicitly requires a management response to 'potentially irreversible changes to the ecosystem as a whole' due to a wide range of possible causal factors. This risks leading discussion on appropriate action into a debate on what actions are irreversible, when an irreversible change has occurred, what elements of the ecosystem are controllable, and to what extent. The above doubts also apply to the suggestion that resources of a marine area should be managed under LME (Large Marine Ecosystem) principles, (e.g., Sherman et al. 1993), by Species Assemblages (Tyler et al. 1982), or even more ambitiously, by Multispecies VPA. This latter theoretically allows the trade offs between exploiters of different ecosystem components to become more explicit, but is extremely data intensive, and at this point is of theoretical interest to assessment of most resources of the type considered here. At a workshop in 1984 on 'Inclusion of fishery interactions in management advice' (Mahon 1985), the participants from the Northwest Atlantic (a well studied area) agreed that "Large multispecies models...were beyond the scope of the resources and manpower of....(fishery) laboratories". There is no evidence that this evaluation needs changing in 1993, and most attempts to incorporate multispecies approaches into fisheries assessment have focused on interactions between two or more components of an ecosystem, and the fleets exploiting them.

68. From a practical management perspective, there is relatively limited experience with management systems deliberately manipulating the relative biomass of ecosystem components, and this approach requires a prior decision about what the relative abundance of the different species in a given ecosystem should be, noting that this may differ considerably from virgin stock conditions without necessarily compromising the survival of any of the species involved. Such changes affect the equity of fleets fishing different resources, and require negotiation between users of different components of the food web (see e.g. Brander and Bennett 1989) prior to selecting species-specific RPs for the ecosystem component in question. Another example of an unresolved contention of this type is the tuna purse seine-dolphin interaction in the East-Central Pacific where

there is disagreement between the 'users' of these interacting resources on the overall harvest rate. As an example of the complexities of species interactions which may nullify comprehensive multispecies approaches, we may note that at a high prey biomass (e.g. of a small pelagic fish, sprat) cod food requirements may be provided for, but large sprat stocks prey on cod eggs! In mixed species fisheries such as most trawl fisheries, attempts have been made to manage a complex of stocks exploited by trawlers using separate trip limits or reference points by species, or 'two-tiered' quota systems as used by ICNAF (see Mahon 1985), where the TAC for all species < the sum of individual species TACs. Neither of these approaches have been without problems and have usually led to high discards.

69. Adjusting the exploitation rate in terms of the natural mortality rate (see Section III) may be an empirical approach that could lead to a set of resource-specific values for fully-recruited resoFs that are relatively invariant. This is more desirable than making F a function of current species abundance which, with variable environmental conditions, would make the fishing mortality TRP a rapidly varying function of environmental conditions. Scaling the species-specific values of F-based LRPs for different food web components according to their relative rates of natural mortality (Caddy and Sharp 1986), remains a theoretical possibility, but one that seems difficult to implement for fishing gears such as bottom trawls that are relatively unselective by species. For such unselective types of gears, a completely precautionary approach for all species being exploited, risks ecosystem exploitation being defined in terms of the species with the least resistance to harvesting; this suggests that developing more selective modes of harvesting is a high priority.

VI. THE SETTING OF MANAGEMENT OBJECTIVES

Multiple options for fishery management

70. Prior to deciding on one or several of the RPs summarized in Tables 4 and 5, the stakeholders in a fishery need to agree on the management objectives for the fishery. Particularly for the stock component within EEZs, these may be decided upon based on a mixture of social, economic or biological criteria, but for distant water fisheries, although economic criteria are important, they are not necessarily shared with the coastal State, and there may also be criteria based on food security or access that are not exclusively economic. Any agreement negotiated on common objectives for managing straddling or highly migratory resources, whatever the underlying national objectives of the participants, will probably have to be spelled out in terms of a technically-defined common reference point. In general, the optima for each objective will differ (see Fig 8), and stakeholders will have to arrive at a compromise which takes into account, to the extent possible, the requirements of all sectors having an interest in the marine environment and its resources. Such an agreement on management objectives may be incorporated into an overall management plan for the fishery which takes into account all relevant factors.

Table 4: The main Reference Points mentioned in this paper; their data needs and bibliographic reference.

R.P.	Theoretical basis	Data needs	Reference
F_{MSY}	Production model	Annual series for Y & calibrated f for all removals.	Hilborn & Walters(1992)
F_{MCY}	Simulation from Annual recruitment series	Popln. param.'s and probability distribution of annual recruitment	Sissenwine (1978)
$2/3F_{MSY}$	Production model	A production model is assumed fitted	Doubleday (1976)
$F_{0.1}$	Y/R calculation and current state of popl.	Population parameters	Gulland & Boerema (73)
Z_{MBP}	Production model	Annual data series of standard catch rate and Z	Caddy and Csirke (1983)
Z*	Simulate overall Z and mean size caught.	Popln. param's; mean death rate/size in popln. & catch .	Die & Caddy (in press)
F_{LOW}	Estimate F giving 90% of years with stock replacement	Assumes data for fitting stock recruitment (usually from cohort analysis)	ICES (1984); Jakobsen (1992)
F_{MED}	Estimate F giving 50% replacement	" " " "	"
F_{HIGH}	Estimate F giving 10% ..... replacement	" " " "	"
$F_{\%SSB/R}$	Analytic model of Biomass /Recruit	Population parameters and maturity-at-age data	e.g. Clark (1991)
F>=M	Empirical (for top predators)	M and sustainable F's for similar resources.	Fisheries literature
F < M	As above (for small pelagics)	" " " "	Patterson (1992)
F_{MEY}	econometric modelling	Historical data on Yield / effort / costs and earnings	Clarke (76) Panayotou (1988)

Table 5: Advantages and disadvantages of mortality-based RPs for management of straddling and highly migratory stocks and their potential applications: (Y = Yes; YY = favoured; N = No; LRP = Limit Reference Point; TRP = Target Reference Point; SR = for Stock Rebuilding - see text)

R.P.	Advantages	Disadvantages	as TRP	as LRP	SR
F_{MSY}	Estimates and historical Y,f series often available	high danger of overfishing as TRP	N	YY	N
F_{MCY}	In theory, allows constant low quota	Data-intensive (info on recruitment variability)	Y	N	Y
$2/3F_{MSY}$	Simply calculated if production model exists	Empirical: needs historical data (Y; f/F)	Y	N	Y?
$F_{0.1}$	well studied: simple to calculate from popl.n parameters	Varies with fishing strategy; sensitive to recruitment level.	Y	N	Y?
Z_{MBP}	Incorporates predation; requires simple historical data on CPUE; Z.	In present form assumes Schaefer model	Y	N	Y?
F_{MSR}	theoretically attractive if stock/recruit data exist	both best Y and F will vary annually	Y	N	Y
Z*	Simply calculated from basic parameters	Needs unbiased data on size frequency of catch	N	Y	N
F_{LOW}	Reflects past probability of recruitment	Needs historical data on stock\ recruitment	Y?	N	Y
F_{MED}	" " "	" " "	Y	N	N
F_{HIGH}	" " "	" " "	N	Y	N
$F_{\%SSB/R}$	Simple to calculate; flexible (depends on %)	No major problems	Y	Y	Y
F>=M	Top predators. Low data needs. (estimate of M).	M values inaccurate. An empirical approach	Y	N	N
F < M	small pelagics. Low data needs (estimate of M).	" " "	Y	N	N
F_{MEY}	Can use production model fit plus cost/revenue data	Hard to define for multiple fleets & varying economic systems\ indicators	Y	N	N

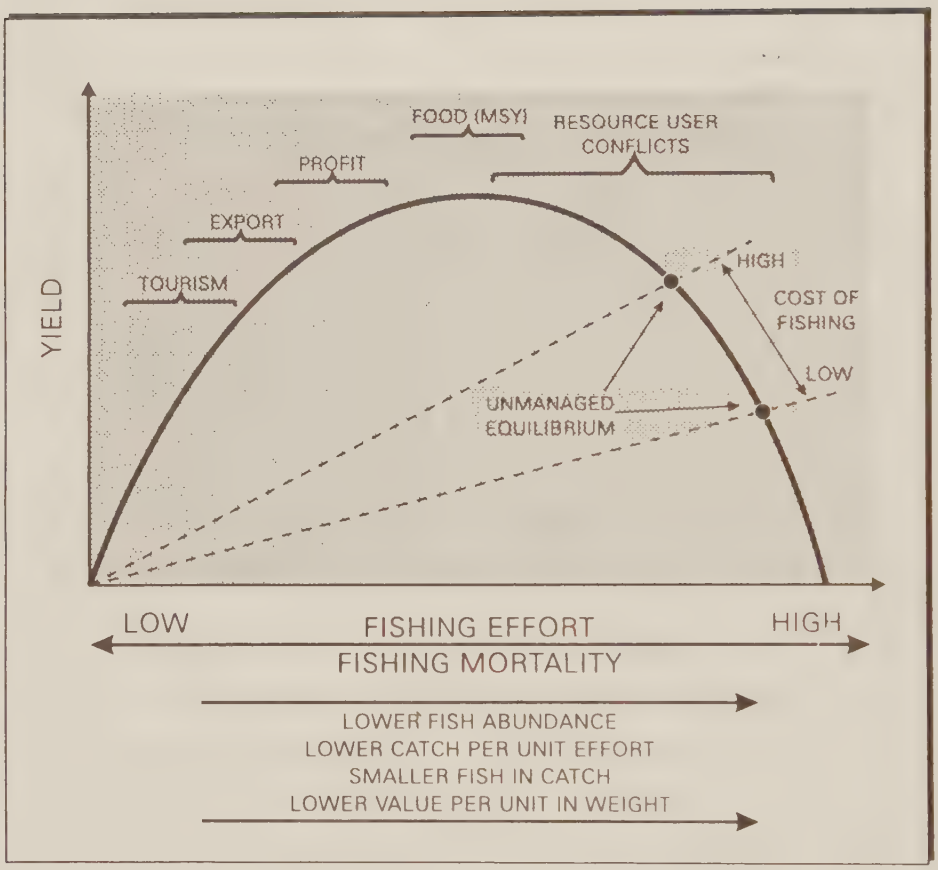

Fig 8: Some relative ranges for the fishing mortality rates corresponding to different uses of marine resources by society (modified after R.Mahon, pers. comm.)

71. Most of the economic activities mentioned in Fig 8 can coexist at medium-high biomass levels, but not at low biomasses. The problem in realizing all of these strategies is that many resources require a period of rebuilding in order that lost options requiring medium-high biomass levels be recovered. For those few resources which still fall in the category of underexploited stocks, precautionary or probing strategies are suggested, which restrict fisheries to fishing intensities well below the likely MSY levels revealed by exploratory fishing, accompanied by intensive data gathering as a requirement for licensing in a 'pilot scale' fishery.

Components of an RP-based management system

72. The setting of management objectives for a new fishery and the actions they lead to, should perhaps follow, with some variations, roughly in the sequence:

1) Exploratory fishing and research
2) The assessment of the state of living marine resources
3) The formulation of management objectives and reference points
4) The negotiation of effort or catch allocations by countries and fleets
5) The framing of an international management agreement and its approval by governments
6) The translation of national legislation into fisheries regulations
7) International or coordinated national provisions for control and surveillance of all participants
8) Provision for the routine collection of statistics and samples
9) The setting of annual targets for the fishery
10) The monitoring of the stock, the fishery, and the enforcement of fishery regulations
11) Review of objectives, research results, assessments and control measures.

73. Some items in the above sequence (e.g., items 3, 4 and 5), although they should be under regular review, will be difficult to achieve for this type of multi-participatory fishery, and renegotiations to revise them may be difficult. Others (e.g., 6, 7 and 8) will need to be reviewed at intervals of several years as conditions change, and items 1, 2, 9, 10 and 11 will need to be reviewed yearly if the optimal benefit from a resource is to be realized, and the probabilities of overshooting the chosen TRP, or entering a dangerous zone, as indicated by an LRP, are to be minimized.

Table 6. Illustration of how different criteria result in a wide range of possible fishing mortality and catch values for a stock (From Gulland and Boerema, 1973). For each criterion, the value recommended by scientists has traditionally been presented without an estimate of risk and uncertainty

Objective and dependence of recruitment on stock size	Optimum F	Catch (t)
Maximum physical yield		
- Constant	1.2	110,000
- Moderately density-dependent	0.9	84,000
- Strongly density dependent	0.6	59,000
Maximum Economic Yield (for given costs and prices)		
- constant	0.8	76,000
- Moderately density-dependent	0.7	68,000
- Strongly density dependent	0.5	50,000

74. It will rarely be the case in the late twentieth century that a new fishery will arise that does not affect existing marine harvests, and where the sequence 1-11 above can be redefined uninfluenced by an existing harvest regime for this or an associated resource, since almost always new fishery objectives in a region are superimposed on or replace old ones, and often follow from the use of a new technology or the need to satisfy a new market demand, there will be calls to revise the objectives of the fishery. Among the reasons for modifying the regulatory framework which is growing in importance, are non-harvest uses of the resource, as a result of the interests of constituencies outside the fishery sector. There is a considerable danger for multi-user resources of frequent changes in objectives, which can lead to time-consuming negotiations and the danger of overexploitation accompanying disagreement between the parties concerned. In the absence of a speedy negotiated settlement on a new reference point and associated management regime, a safe pre-emptive settlement should be arrived at following a precautionary approach. Given the problems of a group of nations arriving at a system such as 1) - 11) above, there should be a strong bias in favour of continuity and conservation, and the avoidance, where possible, of new objectives and untested new technologies.

The role of scientific advice in defining reference points for management

75. Traditionally, the assessment and management of fish stocks has been a two-tier process: scientists present assessments in the form of one or more catch or fishing mortality levels aimed at maintaining or rebuilding stocks, and the managers (Commissioners or representatives of the Ministers of Fisheries of the countries

concerned) make the final decisions on the level of harvesting to be followed. While fishery scientists may be the best qualified to assess the risk involved in any recommendation they present to management, they are aware that considerations of an economic and political nature influence the level of exploitation chosen by the fishery managers. In some fishery management fora fishery scientists have seen that the presentation of a range of possible quota levels results in the selection of one towards the upper level of the range of values decided upon. This type of consideration, and the high degree of uncertainty inherent in the assessment process, has often led to scientific advice being presented to decision-makers not in terms of the uncertainty of the estimates concerned, but as one, or several, explicit levels of fishing mortality or annual catch, each referring to one of a number of alternative management strategies. Gulland and Boerema (1973) give an example of a typical format recommended for presenting alternative management options, where they recognize that although the mortality and catch targets are presented without error terms, they can also be regarded as incorporating different levels of caution. This practice of presenting a single best estimate for a particular strategy without dwelling on its uncertainty, has given a false sense of the precision of the assessment process, and minimized the risks of a stock decline resulting from this level of harvesting. Nowadays, this approach is being replaced by a more explicit recognition of management uncertainty.

Reference points for stock rebuilding

76. One further implication of the above table concerns the continuity of the multi-annual management measures agreed to in following a given management option, for example in stock rebuilding. Since stock rebuilding is not achieved in a single year, F-based RPs corresponding to lower fishing rates need to be assigned some years in advance, and one weakness of most current management systems is their heavy dependence on short-term decision-making. The benefits of losing immediate gains while returning to safer biomass levels do, however, need contemplating and, for example, for relatively long-lived species such as cod and haddock, Rosenburg and Brault (1990) showed that rebuilding over moderate time spans (say five years) is less economically destructive than short sharp reductions in fishing mortality (two year rebuilding scenarios), but that longer rebuilding periods are likely to be too long to see signs of effective recovery. In the case of short-lived stocks, the rebuilding time is likely to be correspondingly shorter. For many stocks which are currently heavily exploited, larger-than-normal cohorts make up a progressively larger part of the annual yield, but may not occur very frequently. Keying in on the protection of these larger-than-normal cohorts may offer the most rapid approach to rebuilding a stock.

Risk analysis and managing by reference points in a fluctuating environment

77. Evaluation of likely risk is always desirable when proposing new management measures (e.g., Beddington 1978; Francis 1991), and while this has been rare in the past, some failures in management of well-studied straddling stocks in recent years have brought this issue to the scientific forefront (see footnote to References).

78. **Risks of overharvesting:** The risks of overharvesting have been described earlier, and range from stock decline to collapse, impacts on associated species and ecosystem destabilization, long-term loss of earnings, including inter-generational impacts. If the conditions for safe harvesting can only be met by expenditures on research, management and enforcement that exceed the net rent likely to be provided by the resource, serious consideration should be given to reconsidering the desirability of sustained harvesting. Under these circumstances when biomass is well above safe limits, intermittent harvesting or culling, under close supervision in years may be a less costly alternative than trying to maintain a low but constant rate of harvesting.

79. **Risks of underharvesting:** The risks of underharvesting are usually defined in terms of the short-term reduction or interruption of steady flow of benefits to participants in the yield fishery and consumers, even though for reasons given below, this may result in a net gain in the long term. Countering such a risk (for participants) may be the rise in market prices resulting from a reduction in supply. Biologically, for species with low natural mortality, yield foregone should be largely available the following year, when the survivors in the unharvested biomass will have increased in individual size, and may have contributed to the recruitment of the stock. Even for species with high natural mortality, the unharvested biomass will make a contribution through predation to other (possibly commercially valuable) components of the food web.

80. **Risks due to environmental fluctuations:** The routine application of RPs in fisheries management would be greatly simplified if environmental conditions remained constant, but most populations show wide variations in annual recruitment, which follow a log-normal or similar distribution function, with a large proportion of the exploited yield coming from a relatively small proportion of year classes. Hennemuth et al. (1980). There is evidence that the chance of one or two very good year classes being succeeded by a string of poor ones, becomes more pronounced as exploitation rate increases, and this is the environment under which it will be necessary to test the performance of the different RPs mentioned above.

81. **Risks due to using the incorrect model:** Four main uncertainties in simulating a fishery have been identified: (a) measured uncertainty in inputs to the model (e.g. catches), (b) perceived uncertainty in inputs and uncertainty due to data-dependent decisions during the analysis, and (c) model uncertainty. Testing a RPs using Monte Carlo simulations of a fishery is becoming more common (e.g. Shepherd and Horwood 1977; Restrepo et al. 1992). Such simulations can also be used to estimate the risks and costs of the management measures proposed, as long as all relevant factors are included in the simulation. In these modelling exercises there is a danger that the wrong model will be imposed on the raw data: some possible examples are the use of models to calibrate indices of abundance (e.g. VPA tuning), the fixing of M values at some conventional constant rate, and the setting of F values for the young fish as a function of that for older individuals. An example, Restrepo et al. (1992), used the Monte Carlo approach to investigate risks associated with quota management of the northern cod fishery. In 1000 simulation runs they found that if at the end of 1990 we wish to achieve $F_{1991} = F_{1990}$, quota values for 1991 anywhere in the range 170 000-260 000t resulted when all elements of uncertainty were introduced into the model. Such a simulation provides the basis for an evaluation of the risk of any given quota: thus they noted that

increasing the quota from 210 000t by 5 000t, doubles the risk of exceeding F_{1990}. Evaluation of risks and costs over longer time periods is highly problematical, since it depends heavily on the assumptions made.

82. **Risk and precautionary approaches**: A management framework that invokes preset actions once one or more (whether qualitative or quantitative) RPs suggest that overexploitation is occurring is (in effect) a precautionary approach. One context for using this was suggested by Die and Caddy (in press) is by analogy to the thermostat: the fishery operating under strict access control, is not subject to a catch target or limitation, but once one or more LRPs or 'rules' show evidence of overexploitation or illegal fishing, a pre-established management action is triggered which reduces the fleet effort. This is maintained or reinforced until the resource shows signs of recovery, as judged by the same criteria, when the effort control may be relaxed somewhat once the fishery is distant from all LRPs.

The uses of RPs with different management strategies

83. A frequent observation of fishery scientists is that although there are a number of useful and safe reference points for management, design of the management regimes which use them is rarely optimal. Such regimes must include a decision-making forum to set guidelines, but the routine management and control and surveillance capability, and the statistical sampling needed to generate objective ongoing information on stock status, must operate largely autonomously, once RPs, 'sets of rules', and consultative and management procedures have been established. In this connection, the lack of definition of interactions between the successive stages in the management process is a serious source of uncertainty which can adversely affect the success of management, as can the use of exclusively short time horizons for determining harvesting strategy. Building learning over time into a management system is also essential. Some of the main management mechanisms which use RPs are described in the following sections.

84. **Open access regimes or the control of fishing?** Many recent studies have emphasized that the open access nature of most marine fisheries has been the principal cause of stock depletion, loss of biodiversity and of potential economic earnings, and of adverse impacts on fishermen's communities. Three types of management measure may be envisaged which control the effort exerted on the stock: (a) Input controls, such as vessel and gear limitations in size and fishing power, restrictions on credit, limited licence or limited access schemes, (b) Output controls, such as restrictions on the total amount of fish harvested annually by the whole fleet (Total Allowable Catches), by individual vessels (Individual Quota Schemes), or by taxes on landings. Such Individual Quota Schemes are often made transferable (ITQs) through the creation of a market for access rights, that as for landing taxes, may be employed by the management authority to extract revenue from the fishery.

85. Three distinct management strategies have been proposed that explicitly or implicitly target reference points, but may optionally also use threshold values to drastically reduce exploitation when stocks are believed to be in danger of overexploitation. These are illustrated in Fig 9.

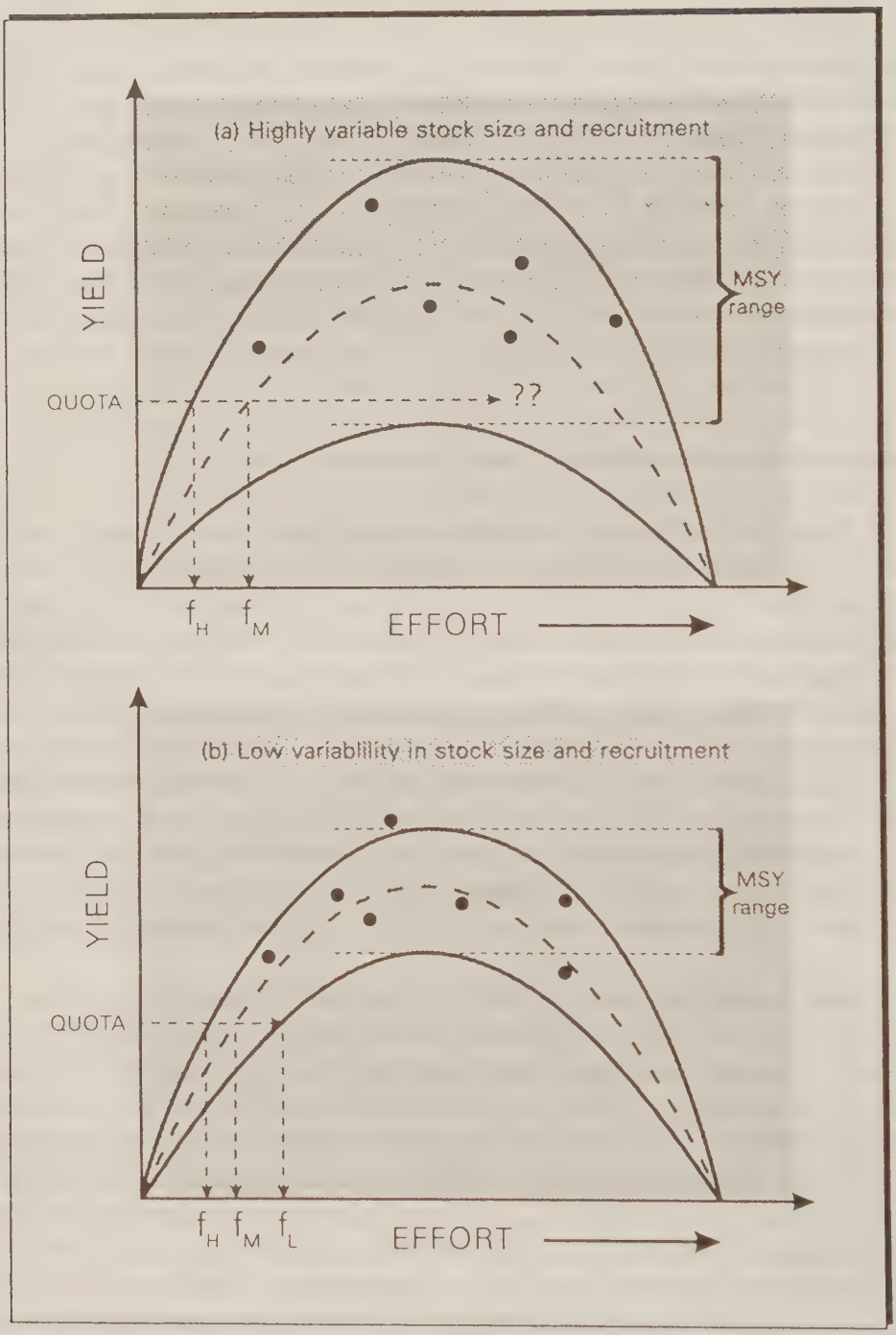

Fig 9: The effects of natural variability on thefeasibility of management by quotas versus effort control. With high population variability (upper), under open access conditions quota control almost inevitably leads to overfishing in years of low abundance, while effort control shows a better performance.

86. **Management using catch quotas to achieve a TRP:** As is shown in Fig 10, for stocks with wide fluctuations in abundance (as for many pelagic resources), a constant catch quota corresponds to constantly varying rates of exploitation, unless it is set at a low level (e.g. the maximum constant quota level mentioned in Sissenwine (1978), which is referred to here as MCY); otherwise, a significant probability of overexploitation always exists. Quotas tend to lag behind by one or several years the actual variations in recruitment, and particularly as good year classes are approaching full exploitation, a quota that would have corresponded to $F_{0.1}$ or even lower levels when the peak year class was entering the fishery, now corresponds to f_{MSY} or even higher levels, and their is marked reluctance by industry to accept a sudden drop in supply under these circumstances. In the North Atlantic, management to date has been largely based on TACs, but there is growing evidence that advice on desirable catch levels has become less reliable due to unrecorded catch and high discards (FAO 1992a). The TAC advised by scientists, that finally agreed after political decision-making, and the actual catches taken, have tended to increase in sequence.

87. If information is scarce or uncertain, then one of the few feasible quota options may be a very low, fixed quota, using TRP criteria developed to ensure a preset probability of F_{MSY} being exceeded (see earlier), or with TRP criteria such as F_{msy} (Sissenwine 1978). This approach could be adapted to straddling stock management, with a cut-off point dictated by one or a series of LRPs which measure when stock size is critical, and the fishery should be temporarily interrupted until unambiguous signs of recovery are seen. Management with such a cutoff point has been successfully applied to herring stocks on the west coast of Canada following a moratorium for stock rebuilding.

88. One of the mandatory requirements for quota management under open access, even at apparently reasonable F levels such as $F_{0.1}$, is the need to ensure accurate, real-time estimates of catch, age composition and standardized fishing effort. The fact that many conservatively-targeted quota management systems have failed, even for proprietary resources of EEZs, should prompt a re-examination of all facets of the management procedure, from considerations of statistical validity of the sampling scheme, the possibility of misreporting, the appropriate population models used, and the accuracy of the parameter values entered in them. The degree to which quotas chosen correspond to the projected fishing mortality rate has been questioned for some developed country fisheries. Even more serious in their effect is the degree to which subsequent catches can be maintained within the quotas allocated, or when politico-economic considerations are allowed to 'stretch' the quotas proposed by fishery scientists.

89. A number of authors have shown the advantages of fixing the level of fishing effort as opposed to fixing catch quotas. Beddington and May (1977) noted that if harvesting for sustained yield is the management strategy, environmental perturbations will cause more serious departures from equilibrium conditions than when a constant effort strategy is followed. This was also the conclusion of Reeves (1974), who also found by simulation, that under recruitment variation, an effort limit produces higher catch rates than a fixed catch quota, even if the latter corresponds to the same RP defined in terms of fishing effort.

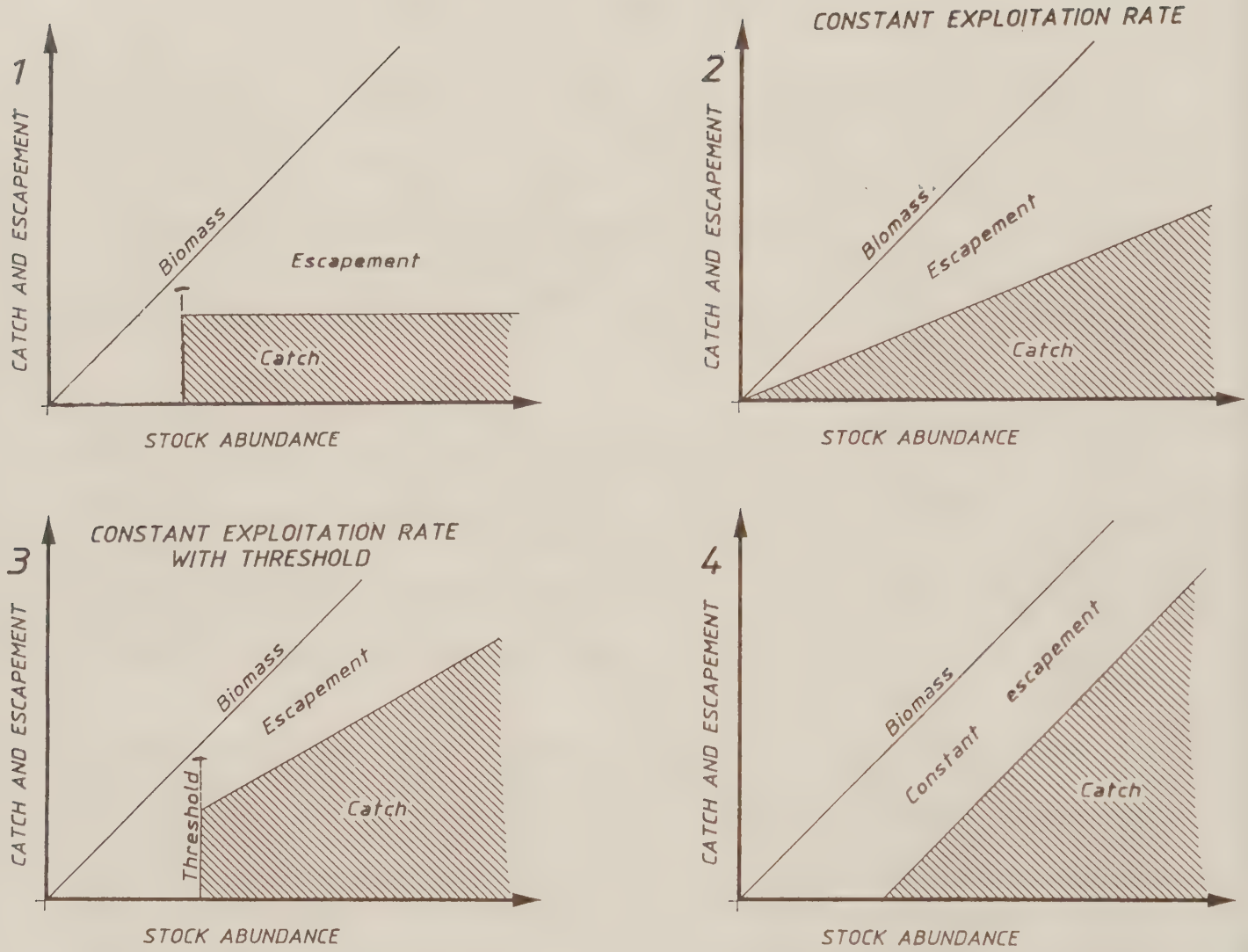

Fig 10: Showing the idealized relationship between catch and escapement under wide variations of stock abundance for 4 management strategies: 1) a constant annual quota with threshold at low abundance when fishing is not allowed; 2) management under a constant exploitation rate; 3) again, a constant effort control scenario with a threshold if natural variation results in very low stock sizes. 4) A constant escapement strategy as attempted for some salmonid and squid stocks.

90. **Management by direct fishing effort control:** This strategy corresponds to one of fishing effort control aimed at a target F value; usually under some system of limited entry. Early criticisms of this approach were the problems of restraining increases in catchability due to learning by skippers and due to technological improvements to boats and gear, that both lead to 'creeping' increases in fleet fishing power. One disadvantage seen in the early optimistic days of quota control, was that under effort control, catches should vary more widely from year to year than with TAC management, but this is still more desirable than stock collapse!. Other more valid objections relate to pelagic stocks such as herring where vulnerability to fishing goes up at low stock sizes, so that the fishery can enter an unstable area unless some limiting LRP is applied, as for the constant escapement strategy mentioned above. The objections to this management procedure need to be reassessed in the light of recent failures of quota control. F-based reference points have been widely used for managing groundfish stocks on the west coast of Canada. Effort control measures have the virtue, especially for poorly documented straddling stocks, that they provide a more stable rate of exploitation, and less need for drastic year-to-year renegotiation of management targets than quota control.

91. **Management with a constant escapement policy:** Salmon management has classically been based on attempting to achieve a minimum escapement to spawning, and many such fisheries in western North America aim for fixed escapement objectives. This type of management approach has also been used for squid fishery management in the South Atlantic within exclusive management control. The management of Pacific coast shellfish fisheries is based on a mixture of size limits, spawning escapement goals and fixed exploitation rates. Such a management approach is compatible with spawning biomass RPs, as described earlier, but is likely to require too high a level of information input for most of the stocks considered here.

92. Clearly, the issue of the appropriate type of management approach to be taken for straddling and highly migratory stocks remains to be decided, but it is concluded that a two-tiered approach always has more chance of staying close to a TRP, namely, to control the number and characteristics of the boats having access to the resource, and at the same time, to closely monitor the state of the fishery with a pre-negotiated response once fishing infringes the LRP(s) chosen.

VII. SUMMARY

93. The various reference points, both existing and proposed in the scientific literature, and their potential for management of straddling and highly migratory stocks are reviewed. Two types of reference points are discussed in terms of the fishing mortality rate to achieve them: target reference points (TRPs) which represent a desirable state of the fishery, and threshold or limit reference points (LRPs) which are markers of the fishery entering an undesirable state, where pre-established management actions to reduce fishing effort come into play.

94. In discussing the use of Reference Points (RPs) for straddling stocks, uncertainties as to the current state of the fishery, and problems of performing joint assessments with data from different gears and fleets, add to environmental uncertainties. Conservative

targets for management are called for, and the paper provides rough estimates of the accuracy with which the current state of the fishery is expected to be known, and touches on the new concern with risk analysis for fish stock assessment. The paper distinguishes two types of reference point: Target reference points (TRPs) which are desirable objectives to be achieved by management, and Limit Reference Points (LRPs), which mark the onset of undesirable conditions, are both referenced to the equivalent rate of fishing mortality needed to achieve them.

95. A discussion of the Maximum Sustainable Yield reference point confirms that, as for the Maximum Yield Per Recruit, F_{MAX} , this is not a conservative TRP unless it is redefined to take into account stock variability, but its possible use as an LRP is supported. Other TRPs that should be considered include the arbitrary marginal yield criterion, $F_{0.1}$, an arbitrary reference point $2/3F_{MSY}$, the spawning biomass/recruit criterion, $F_{\%SS/R}$ (for a fairly high spawning biomass relative to unexploited conditions), and a TRP based on the overall mortality rate (including predation): Z_{MBP} . There is some doubt that available data for most poorly-studied straddling stocks would allow the use of the ICES criteria, F_{MED} or F_{LOW}, despite their desirable properties. The state of depletion of many transboundary resources requires a stock rebuilding strategy, and using a low constant quota strategy (e.g., F_{MCY}) operating with a biomass threshold, or F_{LOW} (based on stock-recruit considerations), may also be appropriate. Where data are poor, analogy with similar resources may require that the fishing rate be defined relative to the natural mortality rate, bearing in mind that this relationship will be different for apical predators and species lower down in the food chain. With our present limited knowledge of offshore ecosystems, defining fishing mortality rates in relation to natural death rates (where known) may be the only feasible approach to multi-species reference points; for most fisheries ecosystems, full multispecies modelling is too data demanding.

96. The possible use of threshold values (LRPs) is discussed, beyond which point the fishery enters a 'red zone' requiring a serious reduction or interruption of fishing. Possible reference points here other than F_{MSY}, are F_{HIGH} (based on stock-recruit considerations), $F_{\%SSB/R}$ (for low biomass values relative to virgin stock conditions), and Z^*; a mean size-based reference point for stocks exploited before age at first maturity.

97. The use of economic criteria as the basis for a commonly-agreed technical reference point, while important for proper use of national resources, presents certain problems at the international level if the exploiting parties owning competing fleets have divergent economic criteria, costs and market prices. There are also problems if the cost of financing investments in the fishery changes from year to year, and a fixed economic criterion is used for determining entry to an open access fishery. A significant degree of over-investment exists in world fisheries, and it is doubly irrational to pursue high rates of exploitation that result in stock collapse as well as economic failure of fishing enterprises. It is on this basis that non-technical criteria such as Optimal Yield while, in principle, desirable objectives for a competitive economic activity, present difficulties as the basis for agreement within international fisheries bodies. Nonetheless, a number of technical reference points such as $F_{0.1}$, F_{MSR} , and F_{MBP} , all share in common a feature of the effort at Maximum Economic Yield, f_{MEY}, namely that they are achieved at a level of fishing mortality lower than that providing the MSY, and hence could be used in absence of a commonly agreed value for f_{MEY}.

98. With respect to highly migratory resources, the criteria for defining a population level RP are common to those of other stocks, namely, an overall stock assessment incorporating removals from all jurisdictions. This may not be sufficient, however, and separate reference points for the age-specific mortalities and yields from each jurisdiction will have to be coordinated to result in a pre-agreed probability of survival to spawning. The proviso to this 'idealistic' scenario is that for most highly migratory species, estimates of stock size at age are very poor.

99. For any stock, choosing an appropriate reference point in absence of information on its management context is inappropriate, and the paper discusses how reference points are used. Managing resources safely under a fluctuating environment and uncertain or inadequate statistical data, requires caution in setting management targets. The risk of exceeding safe effort levels is greater with quota control than when access and effort is limited. The danger of stock collapse due to overexploitation, whatever the steady-state benchmark proposed, is greater for resources with intermittent or irregular recruitment; here, a highly responsive management system is essential.

100. The performance of a reference point under situations of increased uncertainty will depend largely on information generated by the management system and by research, and on the management body reacting promptly to this information. The conclusion is that a precautionary approach when criteria for overexploitation are registered, and prior agreement on what management action to take when this occurs, should be a safer approach than assuming that active management can target the fishery successfully onto some predefined TRP. More recently, attention has been addressed to defining levels of biomass at which reproduction, and/or the biological productivity of the stock remain high. These types of criteria appear to offer a recipe for stock continuity, although some measures are information intensive. In particular, several reproductive reference points require a history of detailed biological statistics, particularly on recruitment, which is not likely to be available for many straddling stocks in the developing world.

101. Most reference points discussed are dependent for their accurate formulation on the validity of the population models generating them, the accuracy of the population parameters used in them, and the confidence level with which the current state of the fishery is known. The value of the natural mortality rate for the exploited stock is a crucial parameter, whose accuracy of determination is usually low, and this affects the accuracy of calculation of many of the reference points proposed. For stocks with very low values of M, well below the financial discount rates of 10% or so that apply for investment in fleet and plant, the fleet size needed for sustainable harvesting is likely to be exceeded, and properly controlled intermittent harvesting schemes may be a better alternative. For straddling stocks intermittent harvesting schemes (either seasons, or rotating harvesting when stock levels are high) should not be discounted as options since they may reduce the costs of surveillance which are particularly high for stocks distant from the coast.

VIII. CONCLUSIONS

102. Management procedures for all types of fish stock should take into account the high degree of uncertainty in our knowledge of the current state of the fishery, in particular with respect to the current rate of fishing mortality and current year class size entering the fishery, caused by incomplete fisheries statistics and environmental variability. An attempt should be made to design management procedures that try to estimate, and take into account, the risk of exceeding or missing the reference point proposed with likely negative consequences to the stocks being exploited. The point is emphasized that, with increased expenditures on research and statistics gathering, a higher rate of harvesting is possible in the same risk of overfishing.

103. It is important for all participants to accept a common objective, common statistical specifications with free exchange of data, and standardized survey and research initiatives. It would be wise to aim for more cautious reference points, especially if misreporting and under-reporting of fishery data or problems of intercalibration apply, as is often the case for straddling and other multi-fleet fisheries. In general, given the difficulty of maintaining a real-time estimate of total landings for all fleets fishing a straddling stock, it is concluded that attempts to manage an open access fishery by quota control alone are likely to fail. It may be wise to adopt a two-tiered management approach with strict control of fishing effort (fleet size, access and/or days fished), and of catch (whether by TAC or by individual boat quotas allocated by time/area strata). New technological developments in monitoring and surveillance should be explored here.

104. Reference points are not necessarily targets for fishery management: in the case of MSY, undetected error will result in 'overfishing' 50% of the time, and this has rendered this particular target reference point a dangerous one for management. The supplementary concept of a limit reference point is proposed that measures when a dangerous zone is being approached or entered. This appears to offer advantages, and such LRP measures can be defined in relation to economic criteria, to stock replacement needs, or in terms of the fishing rate that maximizes stock productivity. All of these measures correspond to a fishing effort significantly below that yielding MSY. In fact F_{MSY} can be used as a limit reference point by agreeing on what fishing rate is likely to exceed F_{MSY} a given proportion of the time with our current state of knowledge of the fishery. If F_{MSY} has already been estimated for the fishery, these kinds of considerations suggest that fishing at between one third and two thirds of the level of fishing mortality that has historically providing MSY, will result in F_{MSY} only occasionally being exceeded, but will not result in a correspondingly large reduction in long term average earnings, and will increase economic returns and minimize ecological impacts and effects on biodiversity.

105. It is stressed that setting a combination of a target reference point formulated in terms of allowable fishing mortality, in conjunction with several limit reference points, each defined, where possible, in terms of independent data sets, should minimize the risk of making dangerous management decisions. At the same time, for many straddling stocks and most highly migratory ones, reference points dependent on high rates of sampling, long historical series, and a large investment in research, are not suitable even if theoretically they offer major advantages.

106. An essential feature of a system involving limit reference points is that contingency plans must be negotiated in advance as to the actions to take if one or several limit reference points reveal symptoms of a state of stock depletion, and allowed to automatically come into operation under such circumstances. Such approaches, using limit reference points or threshold management policies, may properly be referred to as precautionary.

107. Although considerations related to ecosystem health are the subject of intense research at present, in no area of the world's oceans has a multispecies management system operated with a significantly long history of success. Theoretical frameworks for such multispecies management systems are being developed, such as 'tuning' species-specific fishing mortality rates as a function of their relative death rates due to natural causes, but the problems of by-catch, discards, and overexploitation of target and incidental species are multiplied where gear selectivity is poor. A combination of species specific gear and closed seasons and areas when species at high risk occur may have to be designated following responsible fishing guidelines and precautionary approaches.

108. There are a number of possible management approaches where a steady state harvesting in all jurisdictions in relation to a fixed reference point may not be the ideal strategy. This may be the case for stock rebuilding, where ensuring high survival of large year classes may be more efficient than slower rebuilding with a very low steady rate of harvesting. In the case of species whose annual biomass growth is significantly below 10% annually, the high risks of overfishing under open access may suggest intermittent harvesting only in those years when a safe surplus of biomass exists. For highly migratory species occurring in different jurisdictions, not only is coordination of age-specific harvest rates essential, but optimal yield considerations may suggest that harvesting be negotiated between the participants to occur within that part of the stock range where optimal harvesting conditions and sizes are found.

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ANNEX I: The Fishery Models

The Unit Stock

Stock assessment calculations begin at the Unit Stock level; i.e., they consider distinct and separate population units of a single species from which the fisheries yield is, or could be, extracted. A unit stock is more correctly viewed as a self-reproducing population, with limited emigration/immigration to/from other unit stocks. In the case of mobile and migratory stocks which may diffuse or migrate across maritime boundaries, we must include removals from the stock taken from inside all jurisdictions in the initial assessment, since the estimation from the fishery statistics of any single country, of whether an overall RP for fishery yield or standard fishing effort/mortality has been met, is likely to be seriously biased. Also, if a significant component of the catch and effort is not included due to misreporting or non-reporting, this also will result in a high probability that the perceived position of the fishery in relation to the reference point chosen, will be seriously in error.

Global and analytical models and stock-recruit relationships

It is necessary to make a distinction between production models where we only have two trains of annual information: fishing effort and total yield, and where generalizations can be made as to its overall behaviour, but all biological processes going on within the fish population are unknown, and so-called Analytical models, where processes of growth, reproduction and death, subscripted by age, are assumed to be understood and the relevant rates at which they occur are known; the many variants of yield/recruit analysis belong here. Combinations of these two types of models have emerged in recent years, but few applications in practical fishery management have emerged so far. A further type of model that is largely empirical, relates the number of recruits that occur in a year to the spawning stock size (Fig 4). All of these methodological approaches have generated their own model-based management reference points.

The catch equations

The single species theory of fish population dynamics is based on the so-called "catch equations", which postulate mathematical relationships between:

(a) the stock (represented as biomass, total numbers of individuals in those age groups available to fishing (the recruited age groups), or the numbers of individual age groups;

(b) the fishing effort (f) and corresponding fishing mortality (F) it causes; and

(c) the yield in numbers and/or weight resulting from this operation, given that

(d) in addition to fishing, a natural death rate (M) applies, which is the rate at which the stock is being diminished by deaths caused by factors other than fishing (notably predation);

(e) various aspects of the natural history of the species are also pertinent to its capacity to support exploitation.

Two of the most commonly used catch equations are those below, respectively used where the age composition is known (and the subscript t refers to the age of a group of fish), and for the mean population biomass undifferentiated by age, as following the second = sign:

$$Y_t = \sum N_t . w_t . (F/Z_t) . (1-\exp(-Z_t) = \overline{B} . F$$

Both equations contain three interdependent variables (see Fig 1) which are the primary variables available for consideration as possible reference points for fisheries management. These are the fishing mortality F (related to the total (usually annual) fishing effort as F = qf, (where q is the catchability coefficient); the Biomass B, and the fishery yield (usually annual) Y. Since fish stock assessment assigns a primary role to fishing as a cause of mortality, the primary 'control variable' is of course the control of fishing effort and/or fishing mortality, while catch and biomass may under specified conditions of stability and equilibrium, be used as measures of the effects of fishing, and/or measures to indirectly control fishing mortality.

Control of fishing intensity may imply control of the number of vessels of a given type or power allowed in the fishery, and even of the maximum number of standard days fishing allowed. However, for reasons described below, access rights in terms of fleet size and total annual fishing effort has in the past been rarely used directly in negotiations, and has been assumed to be less easily monitored than a fixed catch or quota. Control of the annual yield (despite technical disadvantages at least equal in magnitude), has been the most widely used management practice; perhaps also because it reflects more directly the benefits to be gained by different participants in the fishery. In some fisheries, equivalent benchmarks of economic performance have been calculated, particularly for national fisheries where common measures of economic performance apply. In other circumstances where the levels of total removals, total fishing effort and net economic benefits are difficult to determine, direct survey of the stock is possible, measures based on controlling the biomass of the stock may be more feasible and not liable to biases due to misreporting.

ANNEX II: Using an LRP to set a risk-averse rate of exploitation - the F_{MSY} example

There may be circumstances when fisheries managers are able to specify an upper limit to fishing intensity, beyond which an undesirable state of the fishery is agreed to exist. As noted, this may be referred to as a Limit Reference Point (LRP). For mathematical simplicity we assume in the following, that F_{MSY} is a conventionally-accepted value, known without error. In the following example we further assume that the LRP used in this case is a pre-established 'conventional' value for the fishing mortality corresponding to MSY conditions, agreed to by all parties.

The managers acknowledge that they are operating in an uncertain environment and that the current 'status quo' for the fishery, and the F-value during the last season (= F_{NOW}), were not precisely known, but that some rough estimates of its standard deviation can be made. In the hypothetical case in question, there is strong evidence that the fishing intensity last year was below F_{MSY} , and it is assumed that if the same effort were to be exerted in the next season, we could expect the probability distribution of fishing mortality rates to remain the same. The managers feel however that it would be useful to define a target reference point in such a way that this results in a small, prespecified risk that F_{MSY} is not exceeded.

Given this situation, the following illustrates one procedure for calculating appropriate target values for F_{NOW} which result in a pre-specified probability of an agreed LRP being respected. In this example, the LRP is assumed to be a pre-established value for F_{MSY} = 0.6. There is no unambiguous evidence in the literature as to the most appropriate distribution function describing the uncertainty in the current value of F, but as a first reasonable choice we have used a normal distribution (see Appendix figure below), although similar calculations could readily be performed for other distribution functions.

Mathematically the suggested procedure is the following: The level of risk the fishery can safely tolerate (quantified in the Appendix figure as the shaded area on the right hand tail of the normal distribution), is equivalent to the probability that the current F exceeds the target reference point, F_{NOW}. Referring to this chosen level of acceptable risk as P ($F > F_{MSY}$), we must solve for the mean of the distribution; i.e. the value of F_{NOW} that corresponds to the target reference point providing this margin of safety. The cumulative probability for the right hand tail of the normal distribution may be written as:

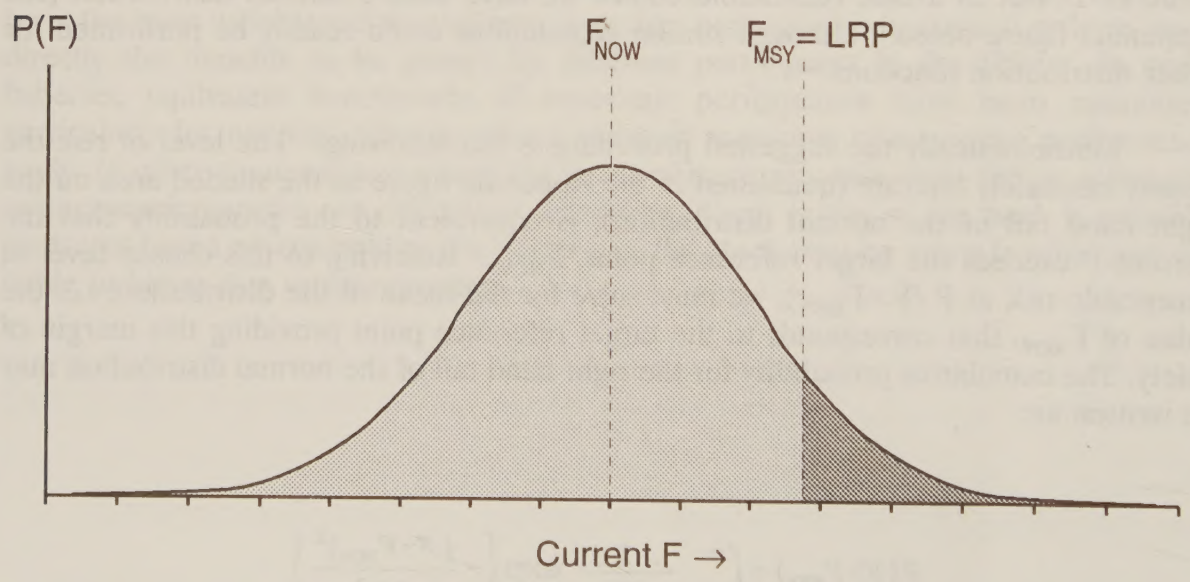
$$P(F > F_{MSY}) = \int_{F_{MSY}}^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left\{ -\frac{(F - F_{NOW})^2}{2\sigma^2} \right\}$$

A mathematical package (MAPLE: Char et al. 1991) was then used to solve for F_{NOW} for the nine cases presented in the table below.

The standard deviation of F, σ, could, in theory, be estimated from the historical record by comparing the predicted Fs and the 'true' values obtained retrospectively from VPA, or by agreeing on a 'likely' level of uncertainty in current F, given estimates of the variance of population size. This type of historical comparison could enable fishery managers to describe more accurately the nature of the distribution in uncertainty of F.

Appendix table: Assuming F_{MSY} = 0.6, the following gives indicative values of F_{NOW} that could be used as TRPs for combinations of (Columns): - The acceptable proportion of the time that F > F_{MSY}, and (Rows): - standard deviations of F.

$P(F_{NOW} > F_{MSY})$	Standard Deviation of F values		
	σ = 0.25	= 0.5	= 1.0
30%	0.53	0.475	0.39
20%	0.50	0.42	0.33
10%	0.45	0.365	0.26



Appendix Figure: Illustrating the uncertainty as to the present rate of fishing, F_{NOW} in relation to a Limit Reference Point (in this case, assumed to be F_{MSY}). A finite probability P(F) of F > F_{MSY} is represented by the shaded right hand limb of the normal distribution.

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